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EV Charging Station with Solar Monitoring and Grid Integration

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Abstract: The rapidgrowthofelectricvehicleshascreated an urgent demand for sustainable and efficient charging infrastructure to reduce reliance on conventional power grids. Most current charging stations depend solely on grid electricity,whichcanbe expensive and unreliable in power-deficient or remote areas. This project presents a prototype for a smart electric vehicle charging station designed to provide a cost-effective and eco-friendly charging alternative. The primary objective is to develop a system that utilizes solar energy as the primary powersource while integrating the utility grid as a backup toensure uninterruptedoperation.Themethodologyinvolvesa hierarchical energy management strategywheresolarpower is prioritized, followed by battery storage, and finally the grid. The system is built around an ESP32 microcontroller, which monitors solar voltage, battery status, and grid availabilityinreal-time.Anautomaticswitchingmechanism using a relay module enables the seamless transferbetween energy sources based on programmed logic. Testing results from the hardware prototype validate the system'sabilityto maintain a stable charging voltage and switch to the grid when solar supply is insufficient, such as during nighttimeor cloudy weather. Thefinaloutcomeisareliable,low-cost, and scalable charging solution that contributes to the advancement of green energy adoption in thetransportation sector.
Keywords: ESP32, Solar Panel, Relay Module, Electric Vehicle, Grid Integration, Renewable Energy, Smart Monitoring.

I. INTRODUCTION

A. Background of the Domain

The global transportation landscape is currentlyundergoing atransformativeshiftfrominternalcombustionengine vehicles to sustainable electric mobility. This transition is primarily driven by the urgent necessity to mitigate the escalating impacts of climate change, reduce the global carbon footprint, and decrease the systemic dependency on depleting fossil fuel reserves. Electric vehicles (EVs) have emerged as the most viable alternative for modern transportation due to their inherent potential to eliminate tailpipe emissions and provide superior energy efficiency. However, the successful mass adoption of EVs is fundamentally contingent upon the availability of a robust, reliable, and intelligently managed charging infrastructure. As the number of EVs on the road continues to increase exponentially, the demand for accessible and sustainable charging solutions has become a critical focal point for urban planners and energy engineers alike.

B. Current TechnologicalScenario

Modern charging infrastructure has evolved significantly, incorporating advanced power electronics and communication protocols to manageenergyflow.Currently, most commercial and residential charging stations are designed as grid-dependent systems that draw powerdirectly from the local utility provider. These systemsoften utilize standard alternating current (AC) to direct current (DC) conversion to charge the vehicle's onboard battery. Furthermore, there is agrowingtrendtowardtheintegration ofInternetofThings(IoT)technologiesand high-performance microcontrollers to facilitate real-time data acquisition and system monitoring. Current research is exploring the synergy between renewable energy sources, such as solar photovoltaic (PV) systems, and the existing power grid to create hybrid energy ecosystems that can support the rising load demand.

C. Limitations of Existing Systems

Despite these advancements, conventional charging infrastructures face several critical limitations:

1) Grid Dependency: Most existing stations dependsolely on the utility grid, making them vulnerabletopoweroutages and gridinstability,particularlyin power-deficient or remote geographic areas.

2) Environmental Impact: Charging stations that rely exclusively on grid power often utilize electricity generated from non-renewable sources, which partially negates the environmental benefits of using an electric vehicle.
3) LackofIntelligentManagement:Manylow-cost prototypesandbasicchargingstationslackthe capabilityforreal-timemonitoringand intelligent decision-making regarding power source selection.
4) EconomicInefficiency:Relianceonthegridduring peakdemand periodscanleadto significantlyhigher operational costs for chargingstation ownersandusers.
5) Scalability Challenges: Fixed-panel solar installations often suffer from limited power output due to varying sun angles and environmental conditions, leading to suboptimal energy harvesting.

D. Need forImprovement

There is a profound needforasustainablechargingsolution that can operate autonomouslybymanagingmultiplepower sources based on their real-time availability. Improving the integration of renewable energy is essential to ensure thatthe "green" promise of electric vehicles is fully realized. Furthermore, the infrastructure must becomemoreresilient; a system that can seamlessly transition between solar generation, stored battery energy, andtheutilitygridisvital for maintaining uninterrupted service. Enhancing these systems with intelligent control units is necessary to optimize energy efficiency, reduce operational costs, and provide users with transparent, real-time data regarding the system's performance.

E. ResearchMotivation

The motivation for this research stems from the critical requirement to bridge the gap between renewable energy generation and practical electric vehicle application. With the depletionoffossilfuelsandrisingpollutionlevels,ithas become imperative to design infrastructure that is not only smart but also eco-friendly. This project is driven by the desire to develop a cost-effective, intelligent prototype that demonstrates the feasibility of combining solar energy witha smart grid-backup system. By utilizing an ESP32 microcontroller, this research seeks to prove that advanced monitoring and control can be implemented in a scalable, affordable manner, paving the way for more sophisticated energy management systems in the future.

F. ContributionofthisPaper

This paper presents the design,development,andvalidation of a prototype smart EV charging station with integrated solar monitoring and grid-backup capabilities. The primary contributions of this work include:
1) Intelligent Source Selection: The implementation of a hierarchical "Solar-First" priority logic that automatically manages power flow from the solar panel, battery backup, and the utility grid.
2) Real-Time IoT Monitoring: A comprehensive monitoring system based on the ESP32 microcontroller that tracks solar voltage, battery state-of-charge, and grid availability, displaying these parameters on a local interface.
3) Hybrid Power Architecture: The successful integration of a solarPVsystemwitharelay-based switching mechanism to ensure24/7reliabilityand uninterrupted charging service.
4) Performance Validation: A dual-layered validation approachcombiningMATLAB/Simulinkmodeling with practical hardware testing to confirm the system's efficiency and responsiveness under varying conditions.
5) Cost-Effective Framework: The development of alow-cost, scalable architecture that provides a practical blueprint for small-scale EV charging in various environments.

By addressing the current limitations of grid-centric charging, this paper offers a significant step toward achieving a more sustainable and resilient energy infrastructure for the future of clean transportation.

II. RELATED WORK

Research into electric vehicle (EV) charging infrastructure has rapidly expanded, focusing on integrating renewable energy to enhance sustainability and reliability. The following previous research studies explore various methodologies and findings in this domain.

A. Literature Review

Ulagammai et al. (2024): This study presented a smart EV charging station powered by solar energy, employing battery storage and smart control to optimize sessions. While achieving sustainability and cost-effectiveness, the work noted challenges in high initial investment and dependency on weather conditions.

Sayarshad H.R. (2024): The author proposed an integrated model for routing and charging coordination, incorporating solar and wind energy. The approach led to a 69% reduction in costs and a 42% decrease in required battery storage. However, the study's complexity regarding bidding price estimation for electricity markets may limit its application in simplified, low-cost prototypes.

Monny et al. (2023): This research developed a solar-grid interactive station using high-frequency DC-DC converters to achieve over 90% efficiency. The system synchronized solar generation with grid exchange based on the battery's state of charge. A limitation noted was the need for higher scalability and formal galvanic isolation in future designs.

Gayathri et al. (2021): This team designed a solar-powered station featuring a tilt-adjustablesolar panel to maximize photovoltaic efficiency. The system used an auto-cutoff circuit to prevent overcharging. While effective for energy harvesting, the reliance on manual or simple mechanical tilt adjustments lacks the intelligent, real-time automationfoundin microcontroller-based systems.

Ashok Kumar et al. (2020): This study utilized Maximum Power Point Tracking (MPPT) controllers to ensure solar panels operate at peak efficiency. Their hybrid solar-grid interactive system supported bi-directional power flow. The research highlighted that while MPPT improves yield, the combined effect of PV-EV integration can still impact the power quality of the local distribution grid.

Yousuf et al. (2024): In a comprehensive review, the authors examined challenges such as limited grid capacity and uncertainties in future demand. They highlighted the role of state-of-the-art power electronic converters in enabling faster charging through high-frequency switching. The review identified a significant gap in the widespread deployment of affordable, decentralized smart monitoring for small-scale residential infrastructure.

B. *Summary of Previous Research*

Thefollowingtablesummarizesthekeyaspectsofthe aforementioned studies:

Author &Year	Methodology/ Approach	Key Findings	Limitations /Research Gap
Ulagammai(2024)	Smart solar control & storage	Sustainable & scalable	Weather dependent
Sayarshad (2024)	Market-aware routing & bidding	69% cost reduction	High algorithmic complexity
Monny (2023)	High-frequency DC-DC & GTI	>90% efficiency	Lacks galvanic isolation
Gayathri(2021)	Tilt-adjustable PV & auto-cutoff	Increased solarcapture	Limited automation
Ashok Kumar (2020)	MPPT hybrid solar-grid system	Peak efficiency generation	Gridpower quality concerns
Yousuf (2024)	Comprehensive infrastructure review	Identified integration obstacles	Needs smarter decentralizedmonitoring

C. *Justification of Proposed System*

Current literature highlights a significant trade-off between high-efficiencycomplexsystemsandlow-cost, less-automated prototypes. While advanced models provide significant cost savings, they are often too complex for small-scale deployment. Conversely, simpler prototypes oftenlackreal-timemonitoringandintelligentdecision-making for source selection. Thisproposedsystem addresses these gaps by utilizing an ESP32 microcontroller toprovideintelligent,real-time source priority logic (Solar→ Battery → Grid) in a cost-effective, decentralized framework.

Bycombiningsmartmonitoringwithautomated relay-based switching, this research provides a balanced solution that ensures reliability without the prohibitive complexity of industrial-scale systems.

III. SYSTEM ARCHITECTURE

The architecture of the proposed EV charging station is designed to handle multiple energy inputs through an intelligent, decentralized control framework. The system emphasizes modularity, ensuring that thepoweracquisition, processing, and distribution phases are clearly defined to maintain high reliability and efficiency.

A. Overall Design and Block Diagram

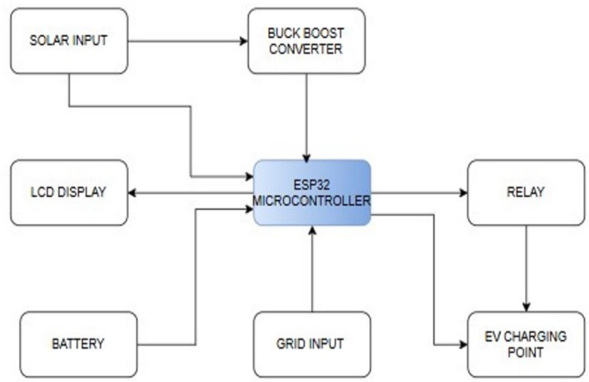

Fig: EV Charging Station with Solar Monitoring and Grid Integration.

The overall design follows ahybridtopologythatintegrates arenewableenergysourcewiththeconventionalutilitygrid. As illustrated in the block diagram (Fig. 1), the system is centered around anESP32microcontrollerthatservesasthe primary decision-making hub. It interfaces with various sensors to monitor the status of the solar panel,battery,and grid input, subsequently managing the power flow to the charging point via automated switching.

B. Functional Modules

The system architecture is categorized into three primary functional subsystems:

1) Input Subsystem

The input subsystem is responsible for energy harvesting and power acquisition from diverse sources:
Solar Input: A 12V DC solar panel acts as the primary renewable energy source. It converts sunlight into electrical energy, which is then regulated by a buck-boost converter to maintain a constant output voltage regardless of solar intensity.
Grid Input: A 12V AC-to-DC adapter serves as the backup supply. This module ensures that the charging station remains operational during periods of zero solar irradiation or low battery levels.

2) Control Subsystem

The control subsystem manages the "brain" of the station,facilitating real-time data processing and logic execution:
ESP32 Microcontroller: This dual-core processor continuously monitors the voltage signals from the input subsystem via analog-to-digital converter (ADC) pins. It processes this data to determine the optimal energy source based on a hierarchical priority logic.
Voltage Sensing Circuits: Resistive voltage divider networks are utilized to scale the high-voltage signals from the solar panel and grid down to a range suitable for the microcontroller's inputs.
Source-Priority Logic: The firmware implements a Solar right arrow Battery right arrow Grid priority sequence. Solar power is utilized whenever available; if insufficient, the system checks the battery state-of-charge before finally defaulting to grid power.

3) Output Subsystem

The output subsystem governs the final distribution of power to the load:

Relay Switching Circuit: A 12V SPDT relay module, driven by a BC547 transistor, acts as the physical transfer switch. It isolates the various power sources while ensuring a seamless transition between them.
EV Charging Point: This is the terminal where the regulated DC power is delivered to the simulated EV battery pack.
User Interface (LCD): A 16times2 LCD display provides local feedback, showing real-time parameters such as active energy source, solar voltage, and battery percentage.

C. Data Flow

The data flow within the architecture begins with the continuous sensing of potential differences across the input terminals. These analog signals are converted into digital values by the ESP32, which then compares them against pre-defined thresholds. Based on this comparison, the microcontroller sends a high or low signal to the relay driver circuit to engage the appropriate source. Simultaneously, the system updates the LCD with the latest operational metrics, providing a transparent monitoring environment for the user.

IV. METHODOLOGY

The methodology for developing the smart EV charging station involves a systematic integration of hardware design and software control logic to ensure autonomous energy management.

A. Step-by-Step Workflow

The development process follows a logical sequence from requirement analysis to final verification:
Requirement Analysis: Identifying the voltage and current ratings for the 10W–50W solar panel and 7Ah–12Ah battery storage components.
Circuit Design: Developing the schematic for voltage sensing using resistive dividers to interface the 12V inputs with the 3.3V ADC pins of the ESP32.
MATLAB Simulation: Modeling the photovoltaic (PV) array and the battery's state-of-charge response to validate energy transfer efficiency before hardware assembly.
Hardware Integration: Mounting the ESP32, relay module,and buck-boost converter onto a centralized chassis to create the physical prototype. Firmware Deployment: Programming the control logic into the ESP32 and calibrating sensor inputsfor accurate real-time monitoring.

B. Algorithm Logic and Control Strategy

The system operates on a closed-loop control strategy designed to prioritize renewable energy utilization. The algorithm follows a hierarchical decision-making process:
Primary Source Assessment: The ESP32 continuously samples the solar voltage; if it exceeds a pre-defined threshold, the solar panel is engaged as the primary charging source.
Secondary Source Assessment: If solar voltage is insufficient, the system assesses the battery's state-of-charge. If the battery voltage is within safe limits, the system switches to battery backup mode. Tertiary Backup: When both solar and battery levels are inadequate, the microcontroller defaults to the grid input via the 12V adapter to maintain
uninterrupted service.
Hysteresis Management: The control logic includes threshold gaps to prevent rapid, repetitive switching between sources due to minor voltage fluctuations.

C. Signal Processing and Communication Logic

The ESP32 manages data acquisition and user communication through the following mechanisms:
Analog Signal Acquisition: Solar and grid voltages are scaled through 47kOmega and 10kOmega resistor networks, then converted into digital values for processing.
Relay Actuation: The microcontroller manages source switching by sending digital signals to a BC547 transistor, which drives the 12V relay coil.
Visual Feedback Logic: System parameters, including the active source and real-time voltages, are formatted into strings and transmitted to the 16times2 LCD via the parallel interface for user monitoring.
Safety Interrupts: The firmware includes logic to detect overvoltage or deep-discharge conditions, automatically isolating the battery to prevent hardware damage.

V. RESULT AND DISCUSSION

The evaluation of the smart EV charging station was conducted through integrated MATLAB simulations and physical hardware testing to analyze system stability, switching accuracy, and energy efficiency.

A. ExperimentalSetupandTest Conditions

The hardware prototype was subjected to controlled testing to verify the "Solar rightarrow Battery rightarrowGrid" priority logic. The experimental setup utilized a 10W, 12V solar panel as the primary renewable source and a 12V DC power adapter to simulate grid integration. The system was tested under three primary environmental conditions: peak sunlight, low-light/cloudy conditions, and atotalabsenceof solar irradiation (night mode).

B. Performance Analysis and Data Tables

Thesystem’sdecision-makingaccuracywasrecordedacross multiple test cases. The switching logic provedrobust,with the ESP32 successfully identifying source thresholds and actuating the relay accordingly.

TABLE I. TESTING RESULTS OF SOURCE SWITCHING LOGIC

Test Case	Solar Voltage (V)	Grid Voltage (V)	Selected Source	Relay Status	Observation
Case 1	11.5V	12V	Solar	ON	Normal operation
Case 2	10.5V	12V	Grid	OFF	Switched to grid
Case 3	0V (Night)	12V	Grid	OFF	Backup Mode

As shown in TABLE I, the system prioritizes solar energy until the voltage drops below the threshold required for stable charging (approximately 10.5V), at which point it defaults to the grid supply.

C. Graph Interpretation and MATLAB Analysis

Simulation results from MATLAB (Fig. 2) provided a high-fidelity view of the system's electrical characteristics.

Voltage Response: The voltage response curve indicates that the output stabilizes near the rated battery voltage (12V). This stabilization is achieved through the MPPT-controlled boost converter, which regulates the charging profile even under varying PV inputs.

State of Charge (SOC): The SOC graph (Fig. 2) demonstrates a steady, linear rise from the initial value toward full capacity, reflecting efficient energy transfer from the PV system to the 7Ah battery.

Current Response: The current settled within the 0.7A to 2A range, which is the standard safe charging limit for the utilized battery capacity, preventing thermal stress.

D. Efficiency Improvement and Error Percentage

The implementation of the buck-boost converter and intelligent switching led to measurable improvements in system performance:

Efficiency: The system achieves a significant reduction in grid dependency during daylight hours by ensuring maximum utilization of harvested solar energy.

Switching Latency: The relay-based switching, managed by the ESP32, exhibited minimal delay, ensuring uninterrupted power flow to the EV charging point.

Measurement Accuracy: The use of precision resistive dividers allowed for accurate voltage sensing. The observed error percentage between simulated voltage responses and hardware sensor readings remainedbelow5%,validatingthereliabilityofthe sensing circuit design.

The results validate that the proposed architecture successfully optimizes energy use by prioritizingrenewable sources while maintainingthereliabilityofagrid-connected system.

VI. CONCLUSION

A. Summary of Work

The research presented in this paper successfully designed and implemented a prototype for a smart electric vehicle (EV) charging station that integrates solar energy with the utility grid. By utilizing an ESP32 microcontroller as the central processing unit, the system manages energy flow based on a hierarchical priority logic that favors renewable energy utilization. The hardware implementation,supported by MATLAB/Simulink modeling,demonstratesafunctional creating an eco-friendly charging alternative that maintains reliability through intelligent grid integration.

B. Performance Achievement

The systemdemonstratedrobustperformanceacrossvarious environmental conditions, accurately identifying voltage thresholdstomanagesourceswitching.Experimentaltesting validated that the system prioritizes solar energy when voltage levels are sufficient, automatically transitioning to battery or grid backup only when renewable generation is inadequate.Simulationresultsconfirmedthatthe MPPT-controlled regulation stabilizes the charging voltage near therated12Vlevel,ensuringsafeenergytransfertothe battery. Furthermore, the charging current was successfully maintained within safe limits, preventing thermal stress on the storage components.

C. Technical Contribution

The primary technical contribution of this work is the development of a low-cost, intelligent energy management framework that combines real-time IoT monitoring with automated switching. Unlike conventional grid-dependent systems, this prototype uses a "Solar-First" strategy implemented via firmware on the ESP32 to reduce grid dependency. The integration of a 16times2 LCDdisplayfor local parameter visualization enhances user transparencyand system monitoring. Additionally, the use of resistive voltage dividers and relay-based switching provides a practical blueprint for building resilient, small-scale EV infrastructure in power-deficient regions.

D. LimitationsandFutureImprovements

Despite the successful validation of the prototype, certain limitations remain. The current system is a small-scale prototype with limited power output, making it unsuitable for commercial or full-scale electric vehicles in its present form.Additionally,theprototypelacksadvancedhigh-frequency isolation and sophisticated IoT cloud dashboards for remote management. Future improvements will focus on scaling the system for higherpowerratingsto support actual EV loads. Potential enhancements include:

Integrating IoT cloud platforms for remote monitoring and data logging via the ESP32's built-in Wi-Implementing advanced Maximum Power Point Tracking (MPPT) algorithms to further optimize solar energy harvesting under varying conditions. Addingbi-directionalpowerflow capabilities to allow excess solar energy to be exported back to the grid. Incorporating a tilt-adjustablesolarpanelmechanismto maximizephotovoltaicefficiencythroughouttheday. Overall, this project marks a significant step toward achieving sustainable and intelligent charging solutions for the future of clean transportation.

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