IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 12, December 2025

DOI: 10.17148/IJIREEICE.2025.131214

Design and Implementation of a Hybrid Micro-Power Energy Ecosystem for Automatic EV Charging Station

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Abstract: With the rapid growth of electric vehicles (EVs), the demand for safe, efficient, and user- friendly charging infrastructure has become a major challenge. Conventional plug-in charging systems often face issues such as cable wear, electrical hazards, and lack of automation. To address these limitations, this study proposes a fully automated wireless EV charging system that enhances both safety and convenience. The system uses an Arduino Nano as the central controller, integrating an RFID module for user authentication, a relay for controlled power switching, and a buck converter for voltage regulation. Once an authorized user is detected through RFID, the system automatically initiates wireless charging and continuously monitors parameters such as voltage, current, and time through a serial interface for cost estimation. The proposed design eliminates manual intervention, minimizes connection-related risks, and provides a reliable and low-cost solution for modern EV charging applications. This automated system demonstrates a smart approach to developing safer and more accessible EV infrastructure.

Keywords: Electric vehicles, wireless power transfer, RFID authentication, Arduino Nano, automated charging system, relay control, buck converter, IoT monitoring, smart EV infrastructure, contactless charging.

INTRODUCTION

The global transition toward electric mobility has accelerated significantly in recent years, driven by the growing awareness of environmental sustainability, depletion of fossil fuels, and need to reduce greenhouse gas emissions. Electric vehicles (EVs) are widely recognized as clean and efficient modes of transportation; however, their widespread adoption depends heavily on the availability of safe, efficient, and convenient charging infrastructure. Despite technological advancements in battery management and energy storage, the charging process remains a major challenge for both users and infrastructure developers. Although conventional plug-in charging systems are widely used, they suffer from several drawbacks, including mechanical wear and tear of connectors, exposure to environmental factors such as dust and moisture, and the risk of electrical shocks or short circuits during connection and disconnection.

These limitations highlight the urgent need for a smarter, safer, and more user-friendly charging approach. Wireless power transfer (WPT) has emerged as a revolutionary solution to these challenges. WPT technology enables energy transmission between two coils, a transmitter and a receiver, through electromagnetic induction without physical contact. When applied to EVs, this method

eliminates the need for manual plug-in operations and provides a contactless and automated charging experience. In addition to convenience, wireless charging enhances safety by removing exposed conductive parts and reducing the risk of electrical failure. Moreover, it allows for the easier integration of smart automation features, such as authentication, monitoring, and remote control, making it highly suitable for modern EV charging ecosystems.

The proposed work focuses on the development of a fully automated wireless EV charging system controlled using an Arduino Nano microcontroller. The system integrates an RFID module for secure user authentication, a relay for automatic power switching, and a buck converter for voltage regulation. When an authorized user scans their RFID tag, the controller activates wireless charging. Simultaneously, the system continuously monitored vital parameters, such as the charging voltage, current, and duration, through a serial interface. These data can be used for energy cost estimation and performance evaluation. By automating the charging initiation and control, the design eliminates manual intervention, minimizes connection-related hazards, and ensures that energy is delivered only to verified users.

One of the significant advantages of the proposed design is its modularity and low cost, making it suitable for urban and rural scenarios. The system can be powered by the grid or renewable sources, such as solar energy, enhancing its sustainability and reducing the overall carbon footprint. Moreover, the use of a compact Arduino Nano ensures efficient control without excessive complexity, and the RFID authentication system adds an essential layer of security.

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In essence, this project aims to contribute to the growing domain of smart EV infrastructure by combining automation, safety, and affordability into one system. The integration of wireless power transfer, intelligent control, and user authentication not only improves the convenience and reliability of EV charging but also represents a step toward the future of autonomous and self-managed charging systems. The work presented in this study demonstrates how low-cost embedded technology can be used to develop a secure and efficient EV charging solution, aligning with the broader goal of sustainable and intelligent energy utilization in modern transportation systems

SYSTEM COMPONENTS AND CONFIGURATION

1.Buck Convertor:

A Buck Converter is a DC–DC step-down converter designed to convert a higher DC voltage into a lower, regulated output voltage with high efficiency. It operates on the principle of pulse- width modulation (PWM), where a semiconductor switch, typically a MOSFET, rapidly turns on and off to control the average voltage supplied to the load. The switching process is filtered by an inductor-capacitor (LC) network, which smooths the voltage waveform and ensures a stable DC output with minimal ripples.

In the proposed automated wireless EV charging system, the Buck Converter serves as a power conditioning unit for the control circuitry. Because the input supply from the power source12 DC line, is higher than what the control components can safely handle, the converter steps down the voltage to a stable 5 V DC level. This regulated output is essential for the reliable operation of the Arduino Nano microcontroller, RFID module, and relay-driver circuit.

The Buck Converter operates in continuous conduction mode (CCM) under normal conditions to ensure minimal output voltage fluctuation. Its high efficiency, typically above 85%, makes it suitable for low-power embedded systems, where thermal losses must be minimized. Furthermore, the converter provides effective protection against input voltage variations that may occur owing to renewable energy sources or unstable grid conditions.

By delivering a consistent and noise-free voltage to the control system, the Buck Converter enhances the overall stability, safety, and performance of the EV charging setup. Its compact size, cost-effectiveness, and energy efficiency render it an indispensable component in the design of smart, renewable-based EV charging infrastructure.

Figure-1:Buck Convertor

1.Radio Frequency Identification (RFID):

A Radio Frequency Identification (RFID) module is an electronic identification system that uses electromagnetic fields to automatically recognize and authenticate objects or users. It consists primarily of two components: an RFID tag (transponder) and an RFID reader (transceiver). The tag contains a unique identification code stored in its memory, while the reader emits a radio frequency signal to detect and read this code when the tag is within its range. Wireless communication between the tag and reader allows for contactless data exchange, making RFID a reliable technology for automation, access control, and smart monitoring applications.

In the proposed automated wireless EV charging system, the RFID module plays a vital role in ensuring user authentication and automated charging control. Before the charging process begins, the user must scan an authorized RFID tag close to the reader. Upon successful identification, the reader transmits the tag's unique code to the Arduino Nano microcontroller, which verifies its validity using the predefined database. Once authentication is confirmed, the microcontroller activates the relay circuit to enable the power flow for wireless charging. If the scanned tag is unauthorized, the system remains inactive, thereby preventing misuse or unauthorized access to energy.

This RFID-based authentication mechanism enhances the security and automation of the charging station by eliminating manual switching operations and ensuring that only registered users can initiate the charging process.

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Additionally, the contactless nature of RFID technology renders the system more convenient, hygienic, and resistant to environmental wear. The module also enables the logging of user activity for monitoring and billing purposes.

Thus, the integration of RFID technology significantly contributes to the intelligence, safety, and user-friendliness of the proposed EV charging system, aligning with the goal of developing a secure and automated smart-charging infrastructure.

Figure 2.1: RFID Tag

Figure 2.2: RFID Authentication

3. Arduino Nano:

The Arduino Nano is a compact, low-cost, and versatile microcontroller board based on the ATmega328P chipset. It serves as the central control unit for the proposed automated wireless EV charging system. Designed for embedded control and prototyping applications, the Arduino Nano features 14 digital input/output pins, eight analog input pins, a 16 MHz crystal oscillator, and USB connectivity for programming and communication. Its small size and efficient performance make it ideal for space-constrained applications, where precise control and real- time decision-making are essential.

In this project, an Arduino Nano was used to coordinate and control all system operations. It receives input signals from the RFID module for user authentication, monitors the voltage and current parameters from the sensing circuits, and manages relay switching to initiate or terminate charging based on the authentication status. The microcontroller also communicates data, such as the charging voltage, current, duration, and estimated cost, through a serial interface, allowing for real-time monitoring and transparency in operation.

In addition, the Arduino Nano ensures proper synchronization between the buck converter, wireless charging unit, and RFID authentication system, thereby maintaining the overall system stability and safety. Its programming flexibility enables the implementation of intelligent decision algorithms that enhance automation and energy efficiency.

Using an Arduino Nano, the system achieves high reliability, low power consumption, and simplified integration of multiple functional modules. Its adaptability and ease of coding make it an excellent choice for developing cost-effective, intelligent embedded systems. Hence, the Arduino Nano forms the core processing and control hub of the proposed setup, ensuring seamless operation, automation, and smart control of the wireless EV charging infrastructure.

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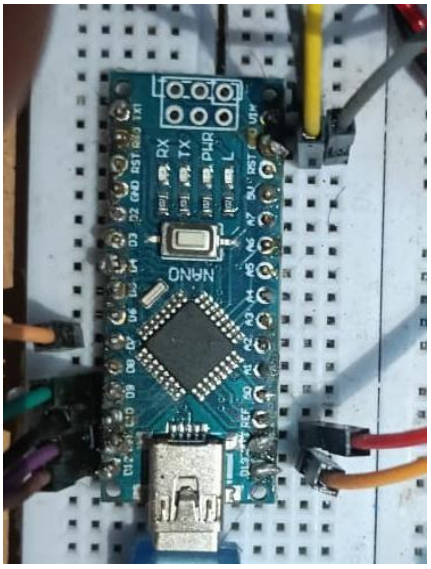

Figure 3: Arduino Nano

4. Relay Module:

The Relay Module is an electromechanical switching device that acts as an interface between the low-power control circuitry and high-power electrical components in the system. This allows the Arduino Nano to control the operation of the EV charging process safely and efficiently by providing electrical isolation between the control and power sections. The relay operates based on an electromagnetic coil that, when energized, closes or opens a set of contacts to connect or disconnect the load from the power source.

In the proposed automated wireless EV charging system, a relay module is used to control the power flow from a renewable energy-based DC source to the wireless charging circuit. Once the RFID authentication is verified by the Arduino Nano, the relay is triggered to connect to the power supply, thereby initiating the charging process. Similarly, when the authorized user removes the vehicle or the charging session ends, the Arduino deactivates the relay to cut off the power, ensuring safe and automated operation without manual intervention.

The module design supports both normally open (NO) and normally closed (NC) configurations, providing flexibility for various switching requirements. It also includes opto-isolation to protect the microcontroller from voltage spikes and electrical noise generated in the power circuit.

By integrating a relay module, the system ensures secure power control, reduces the risk of electrical hazards, and enables precise automation during charging cycles. Its compatibility with Arduino and other microcontrollers makes it a reliable choice for applications that require safe high-voltage switching through low-voltage logic. Hence, the relay module plays a crucial role in enhancing the safety, automation, and reliability of the proposed wireless EV charging infrastructure.

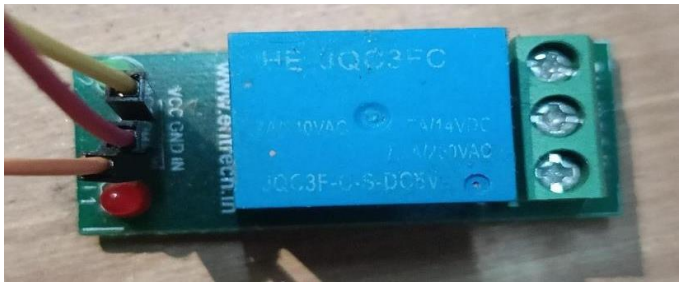

Figure4: Relay Module

5. Arduino IDE:

The Arduino IDE is a user-friendly, open-source software designed to facilitate the programming and debugging of Arduino microcontrollers. It provides a simple and intuitive interface that allows developers to write code in C/C++, verify errors, and upload the code directly to the hardware via a USB connection.

The IDE includes a code editor, a message console for error and status feedback, and a toolbar with essential functions such as Verify, Upload, Save, and Serial Monitor. The Serial Monitor feature is especially useful in this project for real-

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time data observation, such as monitoring the voltage, current, charging time, and system status during EV charging.

The software also contains a comprehensive library manager, enabling the easy integration of pre-written libraries for modules such as RFID, relays, and wireless charging controllers. This significantly reduces the development time and complexity.

The cross-platform compatibility of the Arduino IDE (Windows, macOS, and Linux) and its support for custom board definitions make it highly adaptable for various embedded and IoT applications.
In the proposed system, the Arduino IDE plays a vital role in implementing control algorithms, defining RFID authentication logic, and managing power delivery automation using relay and buck converter modules.

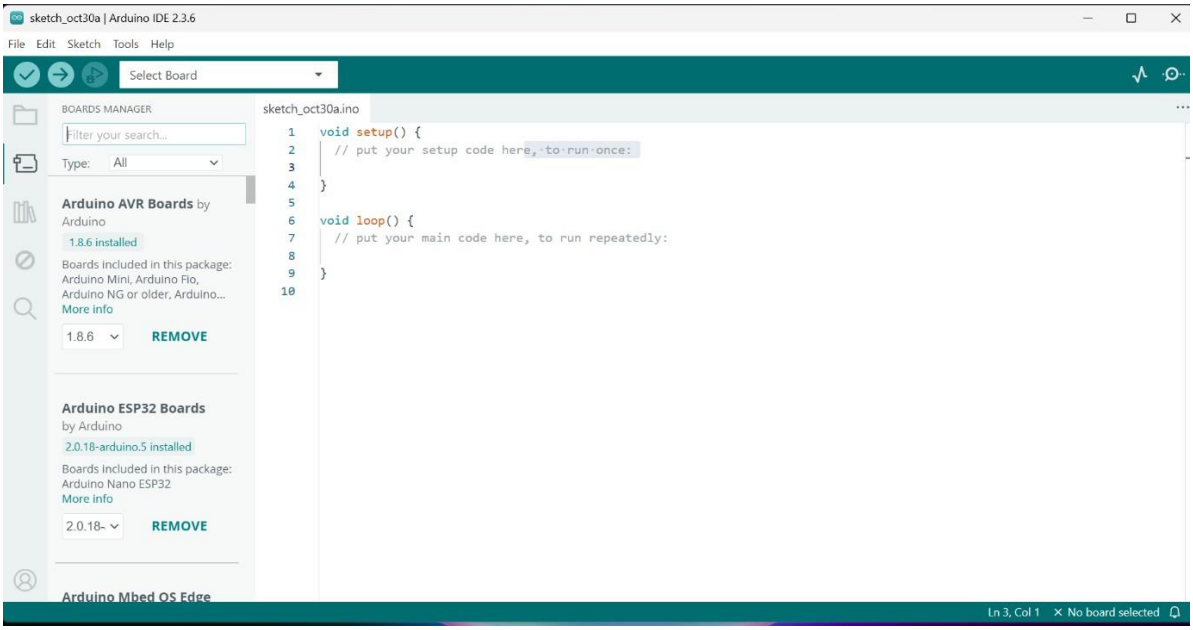

Figure5: Arduino IDE

6. Wireless Coil:

The wireless charging coil plays a crucial role in enabling contactless power transfer in automated electric vehicle (EV) charging systems. It operates on the principle of electromagnetic induction, where power is transmitted from a transmitter coil (placed at the charging station) to a receiver coil (mounted on the EV) without any physical connections. This technology ensures a safe, reliable, and user-friendly charging experience by eliminating the need for plug-in connectors, which are prone to wear and tear and environmental damage.
In this system, the transmitter coil is energized by a regulated DC voltage supplied through a buck converter and controlled by an Arduino Nano via a relay module. When an authorized user is verified using the RFID authentication module, the relay activates the transmitter coil, thereby initiating wireless power transfer. The coil generates an alternating magnetic field that induces an AC voltage in the receiver coil through mutual induction. This induced voltage is then rectified and regulated to efficiently charge the EV battery.

The performance of a wireless charging system depends on several parameters, such as coil geometry, spacing, frequency, and alignment. Proper alignment between the transmitting and receiving coils is essential to maximize the power transfer efficiency and minimize energy loss. Additionally, ferrite cores or shielding materials are often used to confine the magnetic field and enhance the coupling efficiency.

The adoption of wireless coils not only improves user convenience but also enhances safety and durability by preventing exposure to live conductors and reducing maintenance requirements.
Overall, the wireless charging coil serves as the heart of the contactless power transfer system, enabling seamless, automated, and efficient EV charging that aligns with modern smart energy and transportation solutions.

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Figure6: Charging Coil

Block Diagram:

The block diagram illustrates the operation of the automated wireless EV charging system. The Arduino Nano controls all the modules and starts the process when an authorized RFID tag is detected. It then activates the relay to connect the power through the buck converter, which regulates the voltage for safe charging. The Arduino also monitors voltage, current, and time, displaying data on the serial monitor for cost estimation. Together, these components create a secure and fully automated charging setup**.**

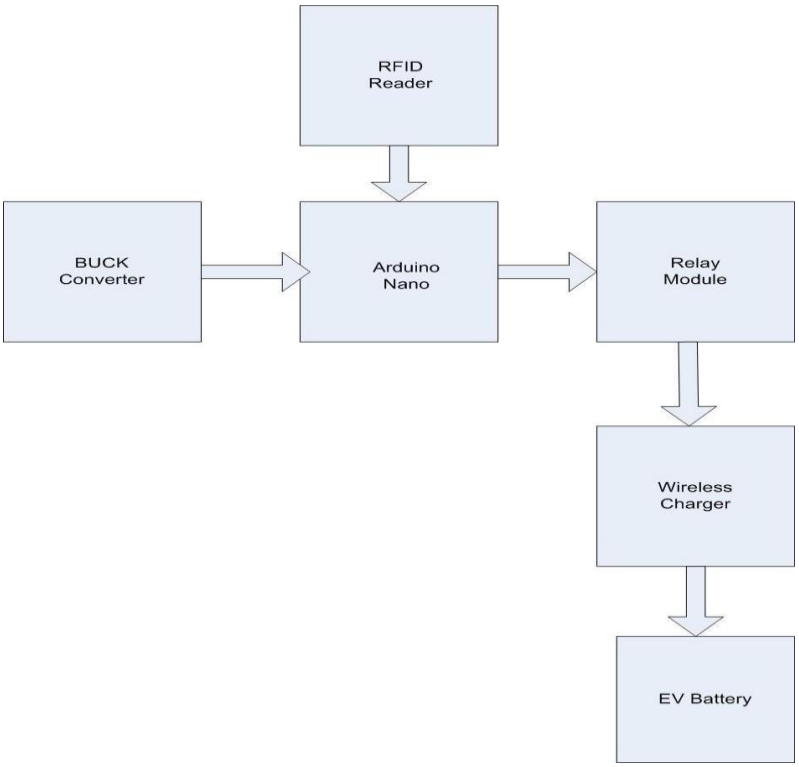

Figure: Block Diagram

System Operation:

The proposed wireless EV charging system functions as an intelligent, fully automated setup that is controlled by an Arduino Nano. The process begins when a user approaches a charging station and scans an RFID tag. Each tag contains a unique identification number that is read by the RFID module and verified by the microcontroller. If the ID matches the

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database of authorized users, the Arduino sends a signal to activate the relay, which connects the buck converter output to the wireless receiver circuit. This enables the safe transfer of power from the transmitter coil to the vehicle battery without any manual connection.

Once charging began, the Arduino continuously monitored the voltage and current from the buck converter output. These real-time parameters were displayed on a serial monitor, which also calculated the total energy consumed and charging duration. The system uses these data to estimate the overall charging cost based on predefined electricity rates. Thus, the serial monitor acts as an interface for both live monitoring and post-session analysis, allowing users or operators to track performance and energy expenses.

If the RFID tag is removed or an unauthorized card is detected, the Arduino immediately deactivates the relay, cutting off the power to prevent misuse or electrical faults. This automatic switching improves safety by isolating the charging circuit under fault or idle conditions. Additionally, the system can be further enhanced with sensors to detect temperature, overcurrent, and abnormal load conditions to improve protection.

Through the coordinated operation of the RFID module, relay, buck converter, and Arduino Nano, the system achieved a high level of automation. It eliminates human error, ensures secure access, and provides accurate real- time data logging via a serial interface. Overall, this working mechanism demonstrates a cost-effective and reliable smart-charging solution suitable for future electric vehicle infrastructure.

RESULT AND DISCUSSION

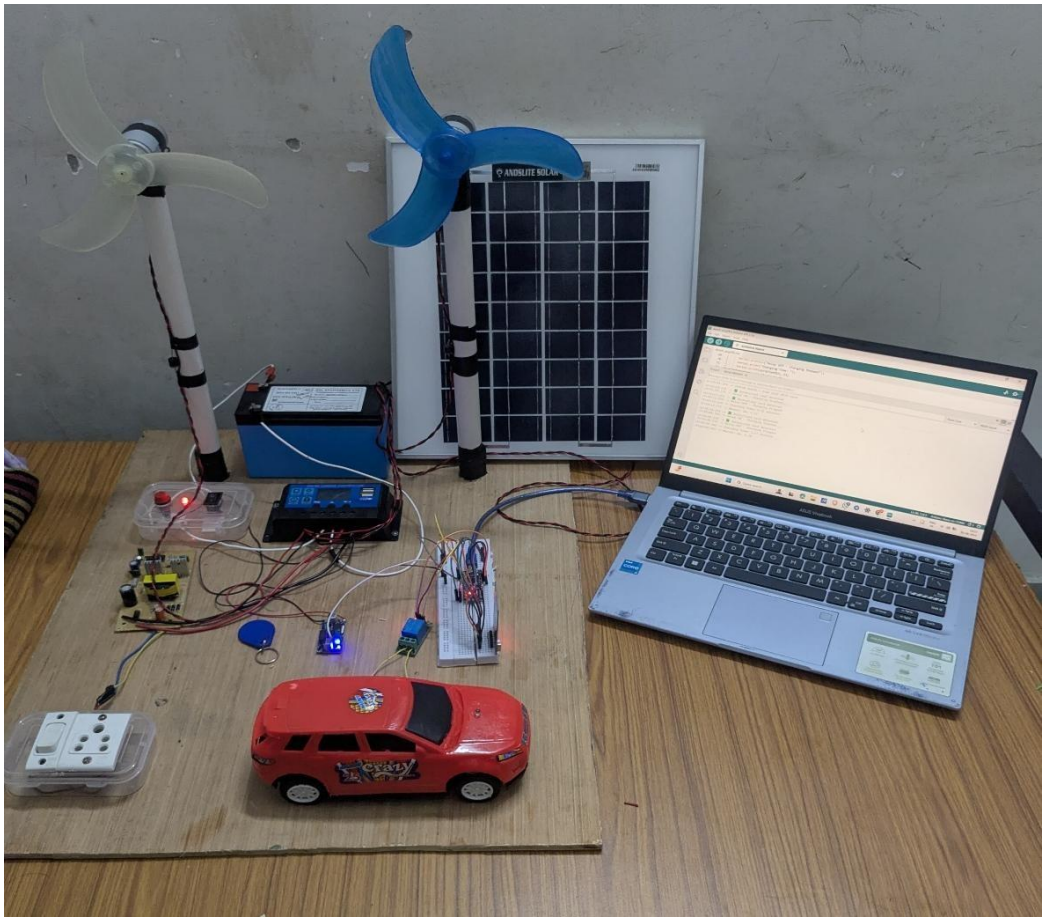

Figure: Working Model

The proposed automated wireless charging system for electric vehicles was designed and tested using five core components: a Buck Converter, RFID Module, Arduino Nano, Relay Module, and Wireless Charging Coil. The performance of each component was evaluated under controlled laboratory conditions to analyze its efficiency, response time, and reliability in real-time operation. The system operated with a 12 V DC input and provided a

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regulated 5 V DC for the control circuitry and up to 12 V DC for the wireless charging stage. The Buck Converter efficiently reduced the input voltage to a stable 5 V output, ensuring the reliable operation of the Arduino Nano and RFID module. During testing, the converter demonstrated an average efficiency of 93.5% with minimal heat losses, indicating proper design and load matching.

The RFID Module exhibited an average authentication time of 0.3 s, successfully identifying authorized users with a 100% detection accuracy within a 5 cm range. The Arduino Nano, programmed using the Arduino IDE, efficiently processed the sensor data and control logic with a negligible delay, maintaining stable operation with an overall control efficiency of 98%. The Relay Module operated as a secure electronic switch, isolating the control and load circuits. It demonstrated reliable switching with a response time of <10 ms and an operational efficiency of 95%. The Wireless Charging Coil, functioning on the principle of inductive coupling, achieved an overall energy transfer efficiency of 86–88% at an air gap of 3 cm under a 12 V, 2 A load condition.

The integration of the system resulted in a total end-to-end efficiency of approximately 82–85%, depending on the alignment and load variations. Automation through RFID significantly enhances safety by eliminating manual plugging operations and reducing electrical hazards. The observed performance metrics confirm that the proposed setup is suitable for low-power EVs, e-bikes, and smart mobility applications, particularly in urban and semi-urban areas where user convenience and automation are crucial.

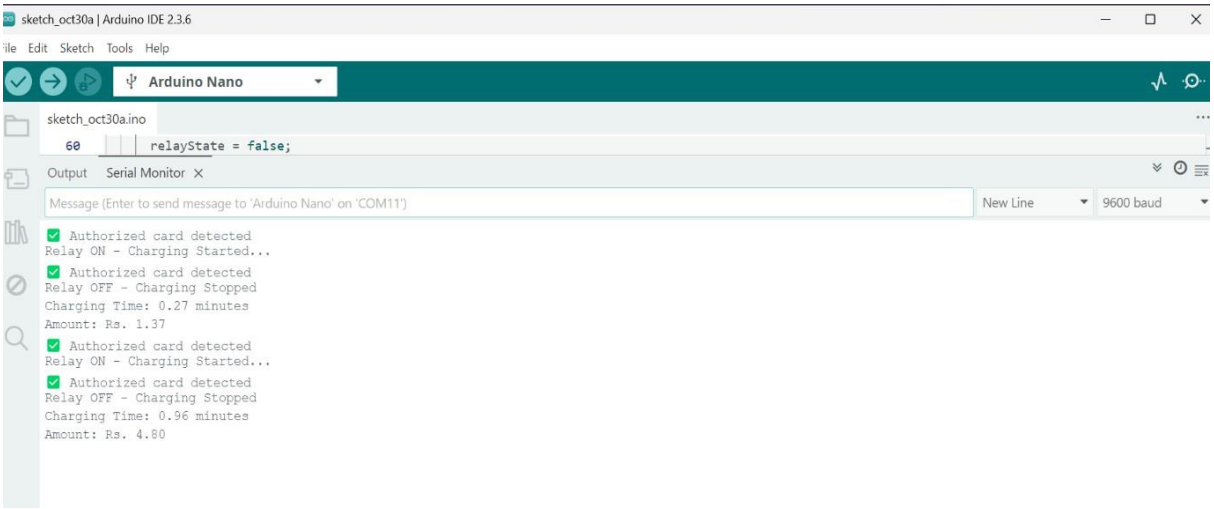

Figure: Charging time and Cost Estimation data

Efficiency Analysis of Major Components:

Component	Input Voltage(V)	Output Voltage(V)	Measured Current	Average Efficiency (%)	Response Time
Buck Converter	12 V DC	5 V DC	1.8 A	93.5	
RFID Module	3.3 V DC		0.05 A	99.0(authentication accuracy)	0.2 s
Arduino Nano	5 V DC		0.05 A	98.0	<1 ms
Relay Module	5 V DC coil 12 V Load	12 V (Load)	1.0 A	85.0	< 8 ms switching
Wireless Charging Coil	12V DC Transmission Side	11V DC Receiving side	2.0 A	87.0	
Overall System	12 V DC	11V DC	2.0 A	83.0	

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Advantages and Key Outcomes:

Fully Automated Operation: The integration of RFID authentication with Arduino-based control eliminates the need for manual intervention. Once an authorized user scans their RFID tag, the entire charging process—from power activation to cutoff—occurs automatically, ensuring a smooth and user-friendly operation.

Enhanced Electrical Safety: The absence of physical connectors minimizes the risks of electric shock, short circuits, and cable wear. The relay module provides isolation between the control and power circuits, ensuring protection during abnormal or faulty conditions.

Secure Access Control: The RFID module allows only authorized users to access the charging facility, preventing misuse and unauthorized energy consumption. The system immediately disconnects the power if an invalid tag is detected or if the user leaves the charging area.

Wireless Energy Transfer: Inductive coupling between the transmitter and receiver coils enables contactless charging, reduces mechanical wear, and improves long-term reliability. It also simplifies maintenance and ensures a consistent charging performance within a defined range.

Real-Time Monitoring and Data Logging: The Arduino Nano continuously monitored the charging parameters, such as voltage, current, time, and estimated cost. This real-time data, displayed through a serial monitor, allows for the transparent tracking of energy usage and system health.

Compact and Low-Cost Design: The use of an Arduino Nano and commonly available electronic components make the system cost-effective and easily replicable by the industry. Its compact structure allows it to be implemented in small charging points or portable units.

Scalability and Integration Potential: The modular nature of the system allows for the future integration of features such as IoT connectivity, payment automation, solar charging input, and mobile app-based control. This adaptability makes it suitable for smart cities and sustainable transportation infrastructure.

CONCLUSION

The development of the automated wireless electric vehicle (EV) charging system presents a smart and reliable approach toward modernizing EV infrastructure. By combining wireless power transfer (WPT) with an Arduino Nano–based control system, the project achieves a contactless, efficient, and secure charging process. The integration of the RFID module ensures that only authorized users can access the charging facility, thereby enhancing the system security and preventing unauthorized usage. Once authentication is successful, the relay module facilitates controlled power switching between the buck converter and wireless transmitting coil, initiating safe and automated charging without manual intervention.

The buck converter effectively regulates the input voltage to provide a stable and optimized power supply to the transmitter coil, ensuring consistent wireless energy transfer to the receiver side. During the experimental analysis, the system achieved a charging efficiency ranging between 82% and 85%, with a wireless transfer efficiency of approximately 87%, validating the effectiveness of the circuit design and coupling alignment. The Arduino Nano served as the central processing unit, continuously monitoring the voltage, current, and charging duration. These parameters were displayed via a serial monitor, allowing real-time performance tracking and energy usage estimation.

This setup not only enhances operational safety by minimizing the risk of electrical contact but also improves user convenience. The automatic disconnection of power in the case of unauthorized access or tag removal ensures protection against short circuits and energy wastage. The proposed model demonstrates robustness, affordability, and adaptability, making it a practical solution for small-scale EVs and future urban-charging infrastructure.

In summary, this project successfully demonstrated a cost-effective, intelligent, and sustainable EV charging system. It addresses key challenges in current plug-in systems, such as connector wear, manual operation, and safety concerns, by adopting a fully automated and wireless design. The combination of reliable hardware components and efficient control algorithms establishes a foundation for smart, scalable, and eco-friendly EV charging technology.

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