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Microcontroller-based Prototype Model of a Solar Wireless Electric Vehicle-to-Vehicle Charging System with Real-Time Battery Voltage Monitoring

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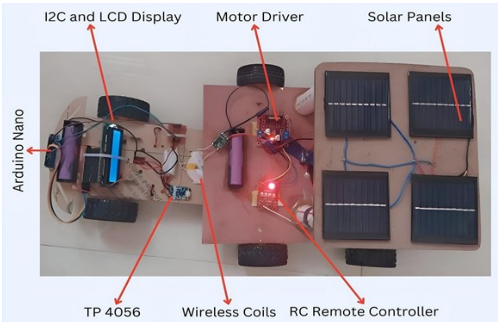
ABSTRACT



The increasing adoption of electric vehicles (EVs) necessitates sustainable and efficient charging solutions, particularly in remote areas and emergencies where conventional grid-based charging stations are inaccessible. This research presents an Arduino-based prototype model of the Solar Wireless Electric Vehicle-to-Vehicle Charging System (SWEV2VCS), integrating a TP4056 charging module, a microcontroller, and wireless power transfer (WPT) coils to facilitate efficient, autonomous charging. The system harvests solar energy through high-efficiency photovoltaic (PV) panels, which are then regulated and stored in lithium-ion batteries. The TP4056 module ensures safe and controlled charging by providing overcharge, over-discharge, and current regulations for battery protection. An Arduino-based microcontroller unit (MCU) is implemented to monitor and optimize power management, ensuring effective energy distribution and preventing inefficiencies. Wireless power transfer is achieved using electromagnetic resonance coupling, which enhances transmission efficiency over short distances. The system employs primary and secondary copper coils designed for resonant inductive coupling, enabling energy transfer between EVs without requiring a physical connection. The design and implementation include real-time battery voltage monitoring using an Arduino Nano and an I2C-based LCD display. The microcontroller measures battery voltage from an analogy pin, processes the data, and displays it on the LCD screen. The voltage sensing mechanism employs analogy-to-digital conversion (ADC) to ensure accurate readings. The LCD module provides real-time updates, enhancing user interaction and monitoring efficiency. The experimental setup verifies system functionality by continuously displaying voltage readings, facilitating better power management during wireless charging. This prototype serves as a fundamental step toward the development of automated, real-time monitoring systems in wireless EV charging applications.

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1. INTRODUCTION
1.1. Background

The rapid growth of electric vehicles (EVs) has fueled the demand for efficient and sustainable charging solutions. Traditional wired charging infrastructures, while effective, face challenges such as accessibility, scalability, and reliance on grid electricity [1]-[3]. In response, wireless power transfer (WPT) and solar-based charging technologies have emerged as promising alternatives, offering enhanced convenience, reduced dependence on fossil fuels, and improved sustainability [4][5]. However, existing charging infrastructures are primarily stationary, limiting their effectiveness in remote or emergencies where charging access is crucial [6]-[8]. Wireless EV charging, particularly when integrated with renewable energy sources, provides a viable solution to address these limitations. WPT technology enables seamless and contactless power transfer, reducing wear and tear on charging connectors and enhancing user convenience. When combined with photovoltaic (PV) energy harvesting, it offers an eco-friendly alternative to grid-dependent charging systems, reducing carbon footprints and promoting clean energy adoption [9]-[11]. Despite significant advancements in both WPT and solar charging, challenges remain in optimizing power transfer efficiency, ensuring system reliability, and addressing mobility constraints [12]-[14].

1.2. Literature Review

Recent research highlights advancements in solar-powered and wireless vehicle-to-vehicle (V2V) charging systems, focusing on system design, efficiency, and practical implementation challenges [15][16]. Table 1 provides a comparative overview of key studies on PV-based wireless EV charging systems, outlining their design approaches and addressed challenges. Studies have explored the architecture and performance of solar-assisted WPT systems, analyzing technical requirements, design constraints, and innovative solutions [22][23]. The combination of WPT with solar energy enables sustainable EV charging solutions that enhance operational efficiency, reduce grid dependency, and improve overall user experience. Key technological advancements include maximum power point tracking (MPPT), optimized power converters, and AI-driven charge controllers [24][25]. Future developments aim to enable dynamic wireless charging, where EVs receive continuous power while in motion, minimizing charging downtime and enhancing mobility [26]-[28]. Table 2 consolidates the comparison between conventional Plug-in charging and wireless EV Charging for different features,

Table 1. Comparison of solar-based wireless charging systems for EVs

Refs.	Approach/Design	Challenges Addressed / Key focus areas
[17]	Energy-optimized solar-powered wireless charging system	Reducing energy losses and enhancing charging efficiency
[18]	Practical design and implementation of energy-efficient WPT	Integration of solar energy with wireless charging
[19]	Optimization of power transfer efficiency in solar-based WPT	Ensuring stable and efficient power transfer
[20]	Implementation of solar-powered wireless chargers for EVs	Managing power fluctuations and extending battery life
[21]	Scalable and reliable solar-based wireless EV charging	Expanding system scalability for larger EV fleets

Table 2. Comparison of conventional and wireless EV charging.

Feature	Conventional plug-in charging	Wireless EV charging.
Charging Method	Physical cable connection	Magnetic field-based power transfer.
Convenience	Requires manual connection	Fully automated, hands-free.
Wear and Tear	Connector degradation over time	No physical contact, and minimal wear.
Safety	Risk of electrical shock, tripping hazard	Enhanced safety, no exposed wires.
Charging Time	Typically, faster	May require optimization for efficiency.
Scalability	Limited by charging station locations	Can be integrated into roads, parking lots, and mobile systems.

1.3. Existing Methods

Stationary EV charging stations are primarily located in urban areas, leaving highways and rural areas underserved [29]. In emergency scenarios, stranded EVs often require towing to the nearest charging station, leading to delays and inefficiencies. While WPT systems provide a convenient solution for contactless charging, they are predominantly stationary and require proximity to charging pads, limiting their applicability in off-grid or emergencies [30]-[32]. Recent efforts have focused on integrating solar power into charging stations to reduce reliance on fossil fuels. However, these systems remain stationary, failing to address mobility challenges. A mobile, solar-powered WPT system could bridge this gap by providing on-demand charging in remote areas. Despite its potential, research on practical implementations remains limited, and further investigation is needed to optimize the efficiency, scalability, and viability of such solutions [33]-[35].

1.4. Research Gaps and Contributions

Despite progress in solar-powered and wireless EV charging, several critical research gaps persist. Current systems are predominantly stationary, restricting their applicability to fixed charging locations. Integrating solar energy with mobile WPT presents engineering challenges, including optimizing power transfer efficiency, minimizing weight, and ensuring real-time energy dispatch [36]-[38]. Another overlooked area is the integration of IoT-based tracking and AI-driven dispatch systems to enhance system responsiveness and efficiency. A mobile charging unit equipped with intelligent tracking and navigation can significantly reduce response times and improve service reliability for stranded EV users [39]. Additionally, user experience remains underexplored, with little research on intuitive interfaces, remote monitoring, and automated notifications to enhance system usability and adoption [40]-[42].

To address these gaps, this research proposes a novel Solar Wireless EV-to-Vehicle Charging System (SWEV2VCS), combining mobility, sustainability, and technological innovation. Unlike conventional stationary charging stations, SWEV2VCS transforms an EV into a mobile charging unit powered by solar energy and WPT technology. This system enhances emergency response capabilities by efficiently locating and navigating vehicles in need of charging assistance [43]. SWEV2VCS contributes to sustainability by reducing grid dependency and integrating PV panels for self-sustained energy harvesting. Additionally, advanced control algorithms ensure stable and efficient wireless power transfer while maintaining safety and reliability. The system's IoT-enabled tracking and AI-based dispatching optimize response times, providing stranded EV drivers with timely assistance [44][45]. By addressing mobility constraints, integrating real-time tracking and dispatch systems, and improving user experience, this research lays the foundation for a transformative shift in EV charging infrastructure. SWEV2VCS represents a significant step toward flexible, efficient, and environmentally friendly charging solutions for emergency and off-grid scenarios, contributing to the broader adoption of renewable energy in transportation [46][47].

2. SWEV2VCS PROPOSED

The proposed SWEV2VCS leverages a solar-powered EV equipped with PV panels to continuously store energy while serving as a mobile charging station for other EVs in need. This system is particularly valuable in remote areas where grid-based charging infrastructure is unavailable, making it ideal for off-grid and emergency scenarios. By integrating renewable energy sources, the SWEV2VCS reduces dependence on fossil fuels and enhances EV accessibility in underserved regions. The system employs WPT technology, based on electromagnetic resonance, to enable contactless energy transfer. This eliminates the need for physical connectors, increasing reliability and simplifying the charging process, particularly in environments where cable-based connections may be impractical. Resonant inductive coupling allows efficient power transmission over moderate distances with minimal energy loss, improving overall system performance. Compared to traditional roadside charging stations, the mobile WPT system offers several advantages [48]-[50]:

- Faster emergency response by enabling mobile charging assistance.
- Improved safety and durability by eliminating physical connectors.
- Increased efficiency by integrating solar energy harvesting, storage, and WPT into a single autonomous charging system.

This innovative approach to emergency EV charging enhances accessibility, sustainability, and reliability, aligning with the global transition to clean energy transportation.

2.1. System Architecture and Components

The SWEV2VCS consists of two main modules:

2.1.1. The Transmitting Vehicle

This EV is equipped with solar PV panels and a WPT transmitter to wirelessly charge other vehicles. Acting as a mobile charging station, it can move toward EVs requiring assistance. Advanced power management systems ensure efficient energy transfer while minimizing dependence on the electrical grid [51] [52].

2.1.2. The Receiver Vehicle

This is an EV in need of an emergency charge. The WPT receiver unit allows it to wirelessly obtain energy from the transmitting vehicle, eliminating the need for direct cable connections. This system significantly reduces charging time and improves accessibility in remote or congested areas. The overall framework of SWEV2VCS is designed to be energy-efficient, safe, and reliable. It employs an intelligent control system to regulate energy flow, optimizing power distribution based on solar energy availability, the changing needs of the receiver, and system status. Additionally, it incorporates protective mechanisms against power surges, overheating, and electromagnetic interference, ensuring seamless operation in diverse environmental conditions [53][54].

2.2. Working on Charging System

An autonomous system is integrated into SWEV2VCS to assist stranded EV users. The system operates as follows [55]:

- Emergency Reporting: The EV user contacts the helpline.
- GPS-Enabled Tracking: The system identifies and dispatches the nearest solar-powered rescue vehicle.
- Wireless Charging: Upon arrival, the transmitting vehicle initiates WPT, providing enough charge for the stranded EV to reach a charging station or complete its journey.

2.2.1. Transmitter Vehicle System

The block diagram of the transmitter system is illustrated in Figure 1. The transmitting vehicle consists of:

- Solar PV panels charge the system's internal battery.
- WPT transmitter coil that generates an electromagnetic field.
- Power conversion circuits to regulate and optimize energy transfer.
- An Atmega microcontroller controls the energy flow and monitors system performance.

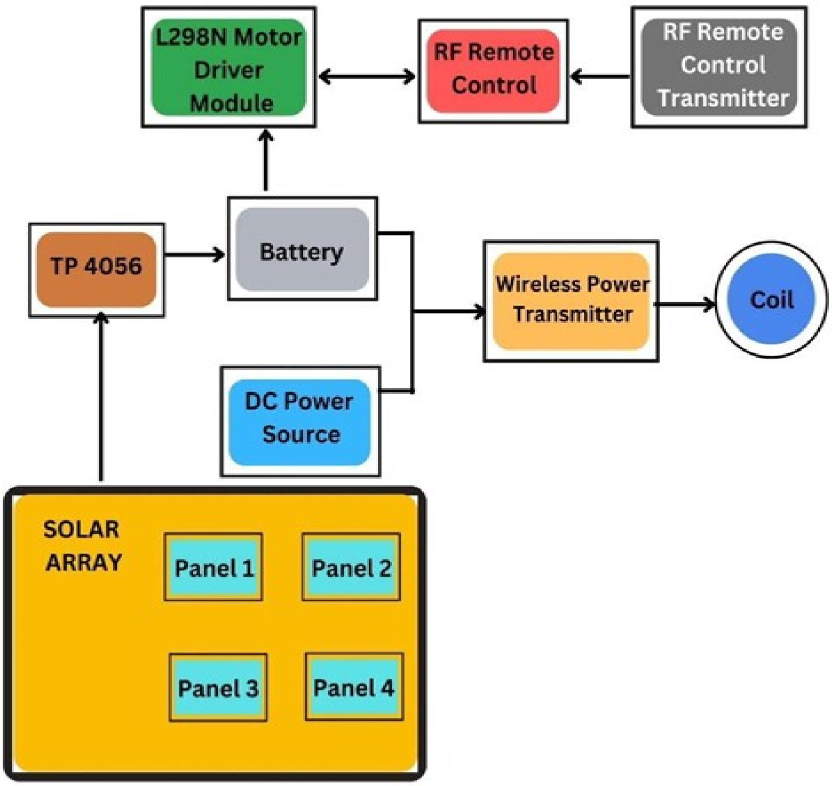

Figure 1. Block diagram depicting components related to transmitting vehicle

2.2.2. Receiver Vehicle System

The block diagram of the receiver system is shown in Figure 2. The receiver vehicle is equipped with:

- A WPT receiver coil that captures energy from the transmitted electromagnetic field.
- A TP4056 charging module to regulate and store the received energy.
- A voltage divider circuit to ensure a stable power supply.
- An I2C LCD module for real-time system monitoring and user feedback.

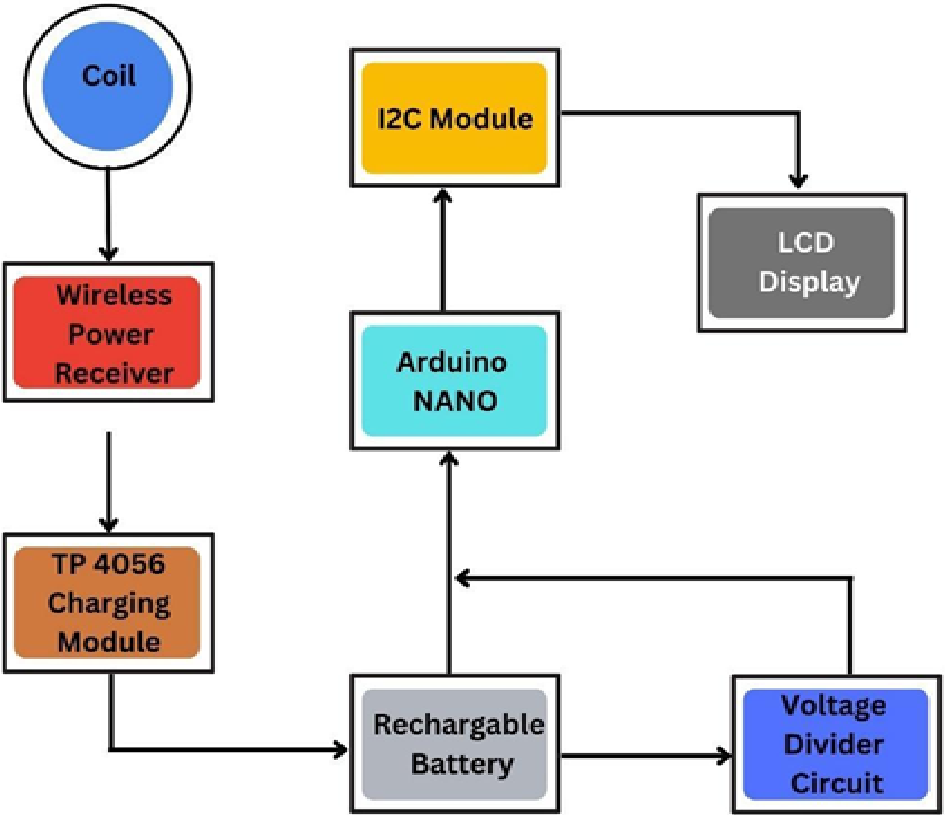

Figure 2. Block diagram depicting components related to receiving EV

2.3. Technical Implementation

2.3.1. Power Conversion and Storage

To maximize solar energy utilization, the SWEV2VCS uses:

- Four 6V polycrystalline solar panels are connected in series to increase voltage output.
- A TP4056 module that ensures safe and efficient battery charging.
- Lithium-ion rechargeable batteries, store energy for later use.

This configuration optimizes solar energy conversion while maintaining stable system performance.

2.3.2. Communication and Control System

The system features:

- Arduino Nano as the main controller, managing power flow and monitoring operations.
- Universal Asynchronous Receiver Transmitter for serial communication.
- I2C and SPI interfaces for efficient data exchange between system components.
- An LCD for real-time monitoring and user interaction.

2.4. Fundamental Equations

The SWEV2VCS system operates as follows:

2.4.1. Energy Harvesting:

PV panels on the transmitter vehicle harvest solar energy, converted using a Maximum Power Point Tracking (MPPT) algorithm to maximize efficiency as presented in Equation (1) [56]-[59]. Where V_{MPP} and I_{MPP} are voltage and current at the maximum power point.

$$P_{max} = V_{MPP}\, I_{MPP} \tag{1}$$

2.4.2. Energy Storage:

Harvested energy is stored in a lithium-ion battery bank, optimized for charge and discharge cycles.

2.4.3. Wireless Energy Transfer:

Power is wirelessly transmitted via electromagnetic resonance coupling as presented in relation (2) [60]:

$$P_T = \eta\, P_{in} \tag{2}$$

Where P_T is transmitted power, η is the efficiency of WPT, and P_{in} is the input power. The coupling efficiency is determined by the coil quality factor as expressed in Equation (3) [60]:

$$\eta = \frac{k \cdot Q_t \cdot Q_r}{1 + k^2 \cdot Q_t \cdot Q_r} \tag{3}$$

where k is the coupling coefficient, and Q_t, Q_r are quality factors of the transmitter and receiver coils.

2.4.4. Power Regulation:

The receiver vehicle's charging module includes a voltage regulator to ensure safe and efficient power delivery as shown in Equation (4) [61]:

$$V_{out} = R_2 \frac{V_{in}}{R_1 + R_2} \tag{4}$$

where V_{out} is the regulated voltage.

3. Prototype Development and Implementation

The transmitting vehicle is the core of the solar-powered wireless electric vehicle-to-vehicle charging system. It is equipped with polycrystalline solar panels optimized for maximum solar energy absorption, which is then converted into electrical energy and stored in lithium-ion rechargeable batteries. An Arduino Nano microcontroller is used to manage the energy flow and control WPT operations, ensuring reliable and safe charging performance. This vehicle enables sustainable mobility and functions as a mobile emergency charger, especially useful in off-grid environments. The different components of this prototype model along with the function of each component are listed in Table 3. The receiving vehicle, on the other hand, is equipped with a receiving coil aligned with the transmitting coil. This configuration enables efficient wireless energy transfer without physical connectors, allowing seamless battery charging while enhancing safety and reliability. A smart control system regulates the received power, ensuring optimal energy utilization and maintaining safe operating conditions. The system integrates several hardware components including. The complete hardware setup demonstrates the feasibility of a compact, mobile, solar-powered WPT system for emergency EV charging. A prototype model (Figure 3) was developed and assembled to validate the concept. Table 4 summarizes the components used and their specifications. It includes both the transmitting and receiving subsystems, which incorporate solar energy harvesting, energy storage, and wireless charging using resonant inductive coupling.

Table 3. Components of the SWEV2VCS Prototype

Component	Function in the System
Solar Panel	Generates renewable energy to power the system
Wireless Power Transmitter	Sends power wirelessly to the receiver
Wireless Power Receiver	Receives energy and transfers it to the EV battery
Arduino Nano	Controls system operations and monitoring
LCD Display	Displays real-time charging status
Voltage Divider Circuit	Adjusts voltage levels for safe microcontroller input

Table 4. Prototype Components and Specifications.

Component	Specification
PV Panel	6V, 10W Polycrystalline
Li-ion Battery Pack	3.7V, 2600mAh
MPPT Controller	Incremental Conductance
Transmitter Coil	100 µH Inductance, 10 cm Diameter
Receiver Coil	100 µH Inductance, 8 cm Diameter
Voltage Regulator	LM7805

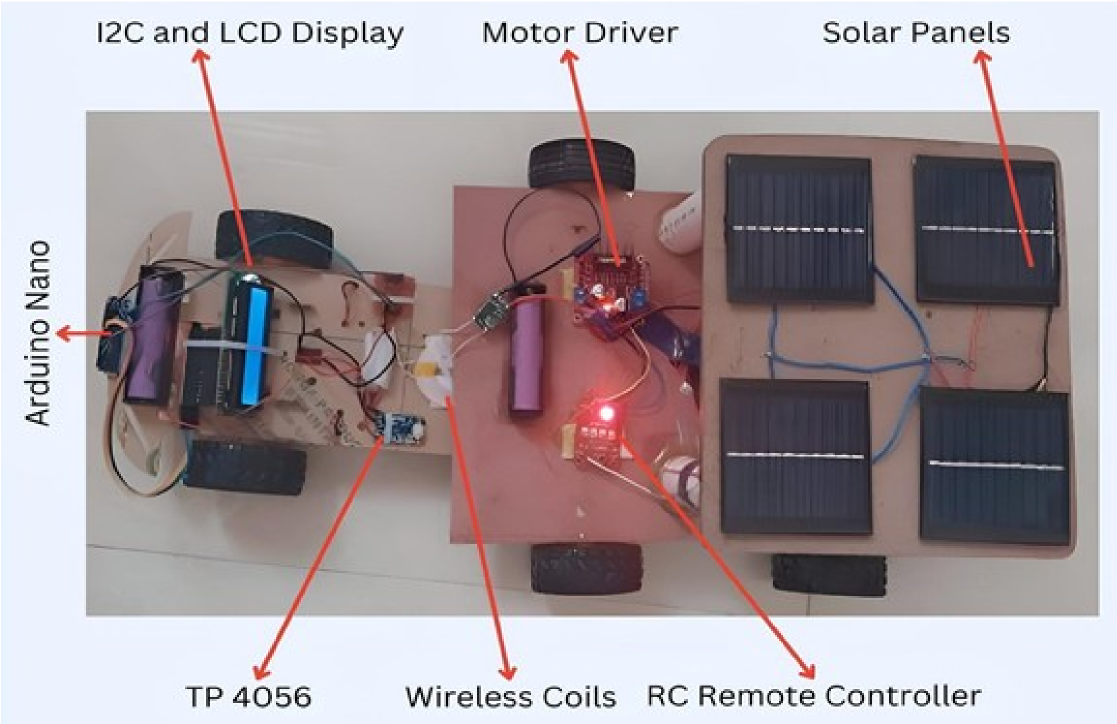

Figure 3. Prototype Model of proposed Charging System

3.1. Arduino IDE and System Programming

The Arduino Integrated Development Environment (IDE) was utilized to program the Arduino Nano, selected for its simplicity, extensive library support, and cross-platform compatibility. The developed code monitors the battery voltage in real-time and displays the output on a 16x2 LCD via an I2C interface, as shown in Figure 4. The advantages of SWEV2VCS in terms of different factors are listed in Table 5.

Table 5. Advantages of SWEV2VCS (Solar Wireless EV-to-EV Charging System).

Advantage	Description
Sustainability	Uses solar energy, reducing dependence on the grid
Mobility	Can be deployed for emergency roadside charging
Ease of Use	Wireless charging eliminates the need for cables.
Modular Design	Can be upgraded with additional features
Scalability	Future expansion possible with AI integration

Key components of the code and system setup:
- Wire.h for I2C communication
- LiquidCrystal_I2C.h for LCD interfacing
- The LCD's I2C address is 0x27, with dimensions 16x2
- The analog pin A0 is used to measure battery voltage
- ADC converts analog readings to digital voltage
- LCD.print() is used to display formatted voltage values
- LCD.backlight() ensures the display remains visible

This setup allows real-time voltage tracking, facilitating intelligent energy management during the wireless charging process.

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

// Set the LCD address to 0x27 for 16 chars and 2-line display
LiquidCrystal_I2C lcd (0x27, 16, 2);

const int batteryPin = A0; // Analog pin connected to the battery

// Function to convert voltage to string
String voltageToString (float voltage) {
  String voltageStr = String (voltage, 2); // 2 decimal places
  return voltageStr.
}

void setup ()
{
 // initialize the LCD
 lcd. begin ();

 // Turn on the blacklight and print a message.
 lcd. backlight ();
 LCD. Print ("Voltage: ");
}

void loop ()
{
 // Read the voltage
 int sensor Value = analog Read(batteryPin);
 float voltage = sensor Value * (5.0 / 1023.0); // Convert the analog reading to voltage

 // Display voltage on the LCD
 lcd. set Cursor (0, 1); // Move cursor to the second line
 lcd. Print(voltageToString(voltage));
 delay (1000); // Wait for a second
}
```

Figure 4. Code in the Arduino IDE

3.2. Output, Observations, and System Behavior

Real-Time Output: The LCD continuously displays the battery voltage, refreshing every second, and providing clear and immediate feedback during charging. Key Results:

- Real-Time Voltage Monitoring: Battery voltage is tracked every second to support responsive energy management.
- Accurate ADC Conversion: Ensures correct voltage computation, vital for safe and effective charging.
- User Interface: The LCD provides a clear visual indication of system status, making it user-friendly even for non-experts.

Prototype Observations:

- Efficient solar energy capture and stable storage.
- Reliable and effective wireless power transfer between vehicles.
- Importance of precise coil alignment for optimal energy transmission.
- Built-in safety protections (e.g., overcharge prevention) functioned as expected.
- Arduino Nano and LCD integration offered a cost-effective, accessible solution for live system monitoring.

3.3. Output Voltage Analysis and Display Optimization

Accurate monitoring of output voltage plays a vital role in managing renewable energy systems. Leveraging the Arduino Nano in conjunction with an I2C-enabled LCD, the system ensures consistent tracking and analysis of output voltage in real time. This proactive approach enables early detection of voltage fluctuations, which is critical for system reliability and component protection. The compact form factor and low power consumption of the Arduino Nano make it ideal for mobile applications, while the intuitive LCD facilitates decision-making and diagnostics.

3.4. Output on Display and Communication Efficiency

The integration of the I2C protocol alongside the Arduino Nano and LCD significantly enhances the system's efficiency and scalability. I2C allows communication with the LCD via just two wires, simplifying connections and preserving digital pins for other peripherals. Benefits of I2C Integration:

- Simplified wiring with fewer connections.
- Improved data transfer efficiency.
- Expanded multitasking capabilities of the microcontroller.
- Scalability for adding future sensors or modules

As shown in Figure 5, this communication setup enables a streamlined interface for real-time monitoring and analysis, making it adaptable for various renewable energy and IoT applications. The challenges and suggested improvements that can be done in the future are tabulated in Table 6.

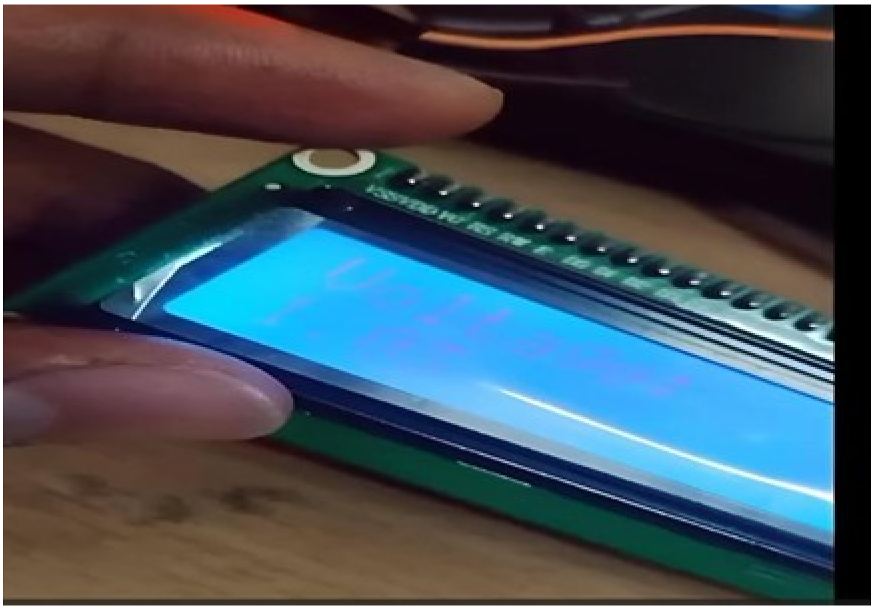

Figure 5. Output Voltage

Table 6. Challenges and future improvements

Challenge	Suggested Improvement
Charging Time	Optimize coil design for better energy transfer
Weather Dependency	Integrate hybrid energy sources (e.g., wind, battery storage)
Compatibility Issues	Standardize wireless charging protocols for different EV models.
Efficiency Losses	Enhance energy conversion rates and reduce transmission losses.
Limited Transfer Range	Improve coil alignment and resonance tuning.

4. CONCLUSIONS

This project develops the SWEV2VCS, addressing key challenges in EV charging by integrating renewable solar energy and WPT technology into a mobile EV charging system. Unlike conventional charging stations that rely on fixed grid-based infrastructure, this system is fully mobile and self-sustaining, ensuring accessibility in both urban and remote areas. The integration of PV panels allows for continuous solar energy generation and storage, ensuring uninterrupted operation without reliance on the power grid. Additionally, WPT technology eliminates the need for physical charging connectors, improving efficiency and safety, particularly in emergencies where rapid charging is required. The system also features an intelligent monitoring interface, which provides real-time voltage analysis and charging status updates via an LCD, improving user experience and system transparency.

Future advancements will focus on optimizing coil designs to enhance energy transfer efficiency over greater distances, making the system even more practical for emergencies. Additionally, the incorporation of hybrid energy solutions, such as wind energy or high-capacity battery storage, will improve reliability in low solar irradiance conditions. AI will further refine charging response strategies, predictive energy management, and system optimization, ensuring faster and more efficient mobile charging services. The proposed work presents a comprehensive approach to the design and implementation of a wireless EV charging system integrated with real-time battery voltage monitoring. By utilizing a microcontroller-based setup (Arduino Nano), I2C LCD, and WPT coils, the system provides an effective solution for wireless energy delivery while continuously tracking battery voltage levels during charging.

DECLARATION

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