

A Self-Sustained Solar IoT Wireless Charging Station for Electric Vehicles: Design, Implementation and Performance Analysis

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Abstract—Most of the traditional EV charging stations are grid connected, and installing charging stations in remote or off-grid areas is challenging because it places strain on the power system. The design and development of Solar Powered IoT Based Wireless Electric Vehicle (EV) Charging Station is presented in this study. It employs 100 W solar PV generation, 85 KHz inductive wireless power transfer (WPT) and IoT. The solar energy goes to a charge controller which steps down the voltage and transfers it to a battery, which then passes the electricity to a wireless charging system, the transmitter coil of which is connected to the receiver coil. The system is controlled by a microcontroller ESP32, Arduino, and voltage and current sensors are used to measure the battery status. These parameters are transmitted via an IoT platform to be monitored, controlled, tracked and diagnosed remotely through a mobile or web app. A test of the prototype was conducted under controlled conditions. The results demonstrate good energy yields, fair efficiency at short distances, and successful real time monitoring. The proposed system is economically viable, environmentally friendly and a smarter alternative to grid alternative charging and can be installed in remote or off-grid areas to decrease the reliance on conventional charging systems.

Index Terms— Solar Energy, Wireless Power Transfer, Electric Vehicle, Internet of Things, Energy Management System, Renewable Energy.

I. INTRODUCTION

A. Background

Electric vehicles (EVs) are gaining popularity worldwide as both individuals and governments seek more environmentally responsible ways to reduce greenhouse gas emissions and combat climate change. The shift from internal combustion engine (ICE) vehicles to EVs plays a critical role in this transition by lowering air pollution, reducing noise, and reducing dependence on fossil fuels such as petrol and diesel. Such characteristics make EVs a part of a green city and the international movement towards net-zero emissions. Among the most important barriers to the introduction of electric vehicles (EV), in addition to the obvious benefits, the lack of

charging infrastructure can be mentioned. The electric car requires a constant and frequent supply of electricity, which may not always be an option, especially in rural or remote locations where the electricity supply is intermittent or non-existent. Most continue to be highly dependent on fossil-based energy sources, such as coal and natural gas, and in well-connected cities, the strain of an increasing number of EVs puts an additional strain on already overloaded power grids.

The current Electric Vehicle (EV) charging model is largely grid based. Most publicly and privately owned charging pads are directly connected to the national electricity supply, which is not reliable in some locations and cannot be maintained in the long term due to carbon footprint. Additionally, economic barriers can occur owing to high electricity prices and peak-hour power consumption and overload utility companies. These problems make it difficult to develop charging infrastructure within a relatively short period, especially in geographically remote locations, particularly in developing countries. Solar energy is free, clean, and can be used anywhere there is sufficient sunlight; hence, it can be used in off-grid or backup energy applications. Additionally, technologies such as wireless power transfer can be adopted to prevent the use of physical cables and connectors and make the charging process more convenient to resist weather conditions and be easy to maintain.

The use of Internet of Things (IoT) capabilities is also compatible with solar power as they can be applied to enhance the capability of charging stations to monitor them remotely, control their functions automatically, track the energy consumption, and perform predictive maintenance. This strategic integration boosts the user experience and improves the efficiency of power consumption and reliability of the system. Figure 1 shows the design and development of Solar Powered IoT-Based Wireless Electric Vehicle (EV) Charging Station.



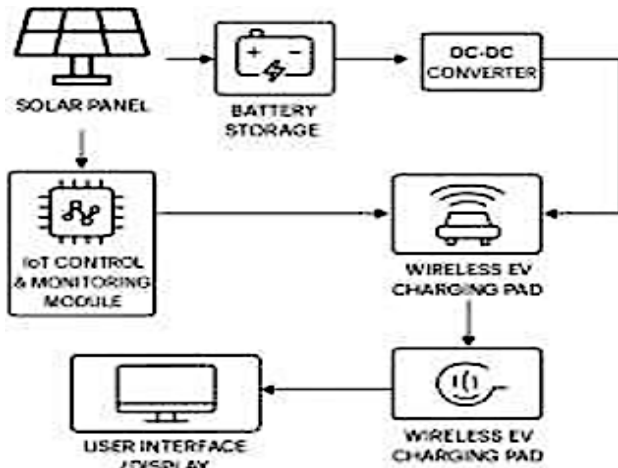


Fig. 1. Solar Powered IoT-Based Wireless Electric Vehicle (EV) Charging Station cycle.

B. System Overview

The concept of this system is the development of a smart and environmentally friendly electric vehicle (EV) charging station that operates solely on solar energy. The concept is to produce a system that does not require connection to the central power grid and hence would be ideal in remote locations, small towns, or standard parking areas where electricity may be scarce or very costly.

The charging station captures energy by means of the sun using the solar panels. The energy is then stored and utilized to charge electric cars. The additional benefit of this system is that it is wireless charging. Therefore, the car does not require plugging in a cable but rather recharges itself automatically when the car is parked on the charging pole. This simplifies it, as well as makes it safer and more comfortable, since there are no longer any wires or connectors involved.

The station is also smart, being wireless and solar-powered. It applies the Internet of Things (IoT) technology to monitor all the things in terms of the amount of solar energy produced, the associated amount of power being charged, battery status, etc. Sensors gather this information, and it is transmitted via the Internet; therefore, users and operators can access the system in real-time via a mobile application or a computer. They will be able to monitor whether the system is functioning correctly, see the power consumption, and even remotely charge it.

The aim is to simplify the process of charging an electric vehicle (EV), make it greener, and more convenient for all. This project is clean and modern because it makes use of solar energy, wireless charging, and smart monitoring to provide the future of transportation in places where the traditional charging station cannot be established with ease.

C. Problem Statement

With the increased use of electrical electric vehicles (EVs), the need for charging stations also increases. However, the majority of existing charging systems rely on old-fashioned electricity sources and wires. This restricts their application and amplifies their impact on the environment. Besides that, users

will find it inconvenient to plug in and unplug cables every time and wear and tear can take place with time.

D. Objectives

The main aim of the project is to design and develop a sustainable, smart, and easy-to-use solar-powered and Internet of Things (IoT)-based wireless electric vehicle (EV) charging station. In order to do this, the following particular objectives are formulated;

- Design and develop a Solar-Powered Charging System.
- Implement wireless power transfer (WPT) to charge the system in wireless mode.
- Reduce the dependencies of conventional charging system.

II. RELATED WORK

Wireless EV charging can allow autonomous charging and reduce battery size and even battery life. This study focuses on the vulnerabilities of wireless charging stations due to compromised EVs and assesses their vulnerabilities using a simulation analysis. In addition, a mitigation plan is recommended to help prepare wireless charging infrastructure for resilience and security [1]. This study describes a wireless and solar-driven charging station for electric vehicles (EVs) that uses Internet of Things (IoT) technology to monitor the charging process in real time. The system contains an Arduino microcontroller with an ESP8266 Wi-Fi module, IR sensors, and voltage sensors. These components are helpful in identifying the presence of a vehicle, tracking the charging status, and managing power efficiently depending on the amount of solar energy available.

A unique feature of this design is that it allows users to keep charging their vehicle from another charging station if they stop charging midway, as long as payment has been made. This guarantees that users only pay for the exact amount of energy that they use, which makes the system fair and cost-effective. By using solar power instead of regular electricity, this technology encourages cleaner, greener, and more sustainable EV charging infrastructure. In the future, this system can be further improved by the addition of augmented reality interfaces and advanced communication protocols, making it even more user-friendly and efficient. [2].

This study regards a dynamic wireless charging for electric vehicles based on resonant inductive electric power transfer. Wireless charging overcomes the limitations of conductive methods and provides the advantages of contactless energy transfer, increased efficiency, tolerance of misalignment, and shorter charging times. Simulations were performed to analyze the performance under actual conditions, with alignment and gap variations. The research marks the potential of wireless charging to promote convenience, efficiency, and sustainability in the EV transportation space. [3]. This paper proposes a Solar Wireless Electric Vehicle Charging System (SWEVCS) to use photovoltaic electricity and wireless power for cable-free electrical power transmission for EV electricity charging. MATLAB simulations indicate that the peak PV output is approximately 500 W, the charging current is approximately 5 A, and the battery SOC is almost 100% by late afternoon. The

results show good charging performance and a decreased need for the grid, where in the future further improvements will be focused on improving the efficiency and scalability of the WPT system. [4]. This study proposes a solar-powered wireless charging system based on a hybrid compensation network and fixed power point tracking (FPPT) to improve the power quality. FPPT has the advantage of minimum THD and power oscillation compared to normal MPPT and allows stable CC and CV charging. MATLAB/Simulink results indicate less distortion with greater efficiency that confirm the effectiveness of FPPT to enable reliable EV wireless charging [5].

A solar-powered wireless EV charging system uses a combination of photovoltaic panels and an induction model to provide clean and cable-free energy for electric vehicles. This approach helps reduce dependence on the grid and supports eco-friendly transport. Key challenges include improving solar conversion efficiency, energy storage, and managing power variations due to changing weather conditions [6]. This study developed a solar-powered wireless EV charging system that uses a 12 V solar panel to charge a 3.7V battery and provide power to a primary coil for inductive wireless transfer. The secondary coil of the EV obtains and rectifies the power to charge the battery of the EV, where an LED indicates active charging. Tests demonstrated a successful short-range transfer of energy; however, the energy transfer was affected by alignment and distance. The proposed system acts as a proof of concept for off-grid, renewable and wireless EV charging that helps to develop sustainable future mobility [7].

The system combines the generation of solar energy, wireless power transmission, and the monitoring of IoT to offer a smart, efficient, and convenient solution for electric vehicle charging. Solar power is used as the primary source and grid backup for continuous operation, and inductive wireless charging eliminates the need for physical connections. Features such as authentication using radio frequency identification (RFID), real-time LCD authentication, fault detection, controlled DC-DC conversion, and automatic source switching provide improved safety, reliability, and ease-of-use. This design is suitable for efficient, sustainable, and intelligent EV charging infrastructure [8].

This study introduces a solar-powered wireless charging system for electric vehicles that aims to reduce the fuel costs and emissions. The setup includes solar panels, batteries, and power electronics, together with copper coils and a controller to facilitate charging even when the vehicle is moving and eliminate the need for dedicated charging stops. The feasibility of a road-integrated, solar-assisted wireless charging scheme for continuous and environmentally friendly EV operation was demonstrated [9]. Inductively coupled wireless charging has been designed and optimized for EVs. However, 50% of the energy transferred to the EVs was lost. It covers system architecture, coil design, resonant circuits, and power electronics with an analysis of mutual inductance, coupling, and losses. Performance calculations consider factors such as misalignment, air gaps, and material losses, and optimization strategies enhance efficiency, which may exceed 90%. This study provides insights into the development of sustainable and efficient wireless EV charging solutions [10]. This study introduces a solar-powered wireless charging system for three-wheeled e-scooters based on a ferrite-less design and series

compensation for size and efficiency. A PI-controlled P&O MPPT was used to optimize the energy extraction from solar panels. Simulations and Experiments 88.5% efficiency at 300 W over 100 mm.

The system is cost-effective, safe, and helps sustainable urban transport activities by lowering emissions and reliance on fossil fuels [11]. This study reviews wireless power transfer (WPT) technologies for EV charging, including inductive, capacitive, and magnetic gear methods in both stationary and dynamic modes. WPT provides safe, convenient, and low-maintenance charging while ensuring efficiency. The research includes system architectures, advantages, issues, EMF safety precautions, and economic viability towards optimization of EV wireless charging systems [12]. This study introduces a Solar Wireless Electric Vehicle Charging System (SWEVCS) based on photovoltaic energy with wireless power transfer. MATLAB simulations indicate a peak power of 500 watts, a charging current of approximately 5 A, and that the battery SOC is fully charged (100%) by late afternoon. The system reduces reliance on the electricity grid and promotes the use of renewable energy, with efforts to scale-up WPT and enhance its efficiency as a key aspect of future research [13]. In this study, a hybrid controller (PI-PSO) is proposed to minimize the power, voltage ripples and current ripples in the EV wireless charging system, so as to enhance the efficiency and battery life of EVs, especially in low temperatures. Simulations in MATLAB/Simulink indicate that the ratio of ripple is reduced by half in 0.031 seconds, proving stable and robust charging performance. [14]. This study presents a solar-powered EV charging system that is wireless using PV panels, energy storage, and inductive coupling for contactless energy transfer. An Arduino Nano is used to monitor the charging, and an LCD is used to show the real-time status. The system allows efficient charging at a short range, decreases the use of fossil fuel, and provides a clean automated solution for sustainable mobility [15].

This study is a review of wireless power transfer (WPT) for EV charging, including technologies, design considerations, and standards. It discusses issues such as misalignment, solutions such as multi-coil setups, and control (dynamic) with efficiencies of more than 90%. WPT has the advantage of reducing infrastructure cost and provides economic viability with future work towards cross-model compatibility and heavy-duty vehicle applications for sustainable transport [16]. Temperature Controlled Smart Charging for Solar Powered EV Charging Stations This study presents temperature control of solar powered EV charging stations, providing optimized heating and charging of the battery to save energy. Using battery thermal dynamics and the method of dynamic charging rate, the system saves the charging cost by 12.5~18.4% and the heating energy consumption by 0.4~6.8%, while maximizing the use of solar energy. [17]. This study is intended to present a new and smart system of using Internet of Things (IoT) to make electric vehicle (EV) charging more sustainable, efficient, and safe. The system integrates three major technologies—solar energy, wireless charging, and IoT-based monitoring—to form a wholesome solution for EV owners and manufacturers. By utilizing solar panels, the system can create clean energy from the sun, lessening the need for regular electricity from the power grid, and can help save the environment. The wireless

charging feature makes it possible for EVs to charge without using physical cables, making the charging process easier and more convenient.

The IoT feature helps to track and monitor the EV's battery in real-time. This means users and manufacturers are able to gain useful information about the battery's performance, identify problems early on, and avert problems such as overcharging, which can lead to safety risks. [18]. This project introduces a Solar Wireless Electric Vehicle Charging System based on solar panels, HF transformer, Arduino controller, LCD display, and battery for the sustainable charging of EV contactless. The system can efficiently handle the solar energy, gives real-time status with the power storage for the excess power for night-time or cloudy conditions, providing an eco-friendly, reliable, and self-sufficient charging solution. This research proposes a solar-powered wireless EV charging system in order to achieve contactless charging, which will reduce dependence on grid. The system enhances safety, convenience, and sustainability, as it is possible to charge vehicles even while they are moving. By combining solar energy and wireless power transfer it provides an eco-friendly and cost-effective solution to promote the development of sustainable urban transport [19]. In this project, a wireless charging station for EV using solar panels and wireless power transfer is presented, which is capable of clean and contactless charging for EVs. The result is a system that is more sustainable, convenient and reliable due to the reduction of the grid and elimination of physical connections. Solar panels, power converters, wireless transmitter-receptor coils and smart monitoring systems are the key components. The design offers an efficient and environmentally friendly solution in the future towards EV charging infrastructure [20].

III. METHODOLOGY

A. Method

The proposed system's methodology includes generating solar energy, wireless power transfer using inductive power coupling, and monitoring through IoT. There are various stages in the development process as described below:

Solar Power Generation System: The first component of the system is a solar PV system that is used to produce renewable electricity. The solar panel is used for converting the energy of the sun into DC electricity. A charge controller with maximum power point tracking (MPPT) controls this energy to harness the most amount of energy from the PV modules, while also preventing battery overcharging and voltage fluctuations. A regulated power is stored in a rechargeable battery where it acts as an energy storage unit. The battery ensures continuous system operation even if it is not exposed to the sun or if there is low solar radiation.

Experimental Solar Conditions: The solar panel was installed outside with no protection from the sun, and was not shaded on purpose. The prototype was subjected to the varying solar conditions in the natural environment. During the prototype tests, however, the solar irradiance and ambient temperature and relative humidity were not instrumentally recorded. Therefore, the reported wireless-transfer efficiency measuring are made on the controlled electrical input condition given in

Table I, instead of on a normalized solar-irradiance condition. Solar irradiation and environmental parameters should be measured concurrently in future experiments for a more stringent comparison of the performance of solar energy under different weather conditions.

Transmitter Coil Design: The transmitter coil is an essential part of the wireless power transfer system. It is made by wrapping an insulated copper wire in a circular spiral. When an alternating current (AC) is passed through the coil, it produces an alternating magnetic field around the coil. The size, number of turns, and diameter of the transmitter coil were determined based on the power transfer and distance to be charged. Ferrite plates were included below the coil, which improved the magnetic flux concentration and thereby increased the transmission efficiency.

Receiver Coil Design: The receiver coil is placed on the side of the electric vehicle or on the wire of the charging module that receives the transmitted energy. It is designed similar to the transmitter coil but can have a different number of turns of wire and coil diameter for optimum coupling.

When the receiver coil is placed in the magnetic field of the transmitter coil the changing magnetic flux will induce an electromotive force (EMF) in the receiver coil in accordance with Faraday's Law of Electromagnetic Induction. This induced voltage is then rectified and used for the EV battery to be charged.

Power Supply and Conversion: The stored energy from the battery is converted into a high-frequency alternating current using an inverter circuit. This AC electricity is fed to the coil of the transmitter, which in turn generates the magnetic field required to transmit energy wirelessly. Stable input conditions for the wireless charging system were ensured by proper voltage regulation.

Frequency Matching: For efficient transfer of wireless power, the operating frequency of the transmitter circuit should be equal to the resonant frequency of the transmitter and receiver coils. This resonance condition makes the energy transfer efficient, and less power losses are experienced. Frequency matching is obtained through the proper selection of circuit elements, such as capacitors and inductors, in the circuit for resonance.

Distance Between Coils: The distance between the transmitter and receiver coil has a significant influence on the efficiency of power transfer. In this project, the optimum distance was maintained within a few centimeters to maximize the energy transfer efficiency. Experimental testing was performed by changing the distance between the coils from 1 cm to 6 cm to evaluate the system performance.

IoT Monitoring and Control: Microcontroller ESP32 was used to control the system and gather operational data. Sensors were used to measure the voltage and current during the charging process. The collected data are sent through an IoT platform, which allows them to be monitored in real time, controlled remotely, and analyzed in terms of performance via a mobile or web-based interface.

System Testing/Performance Evaluation: The final stage of the methodology was to perform tests for the performance of

the wireless charging system. Several parameters, such as voltage drop, current variation, and output efficiency, were measured at different distances between the transmitter and receiver coils. To build a solar-powered, wireless, and IoT-enabled EV charging station, followed a practical stepwise approach. The project began with planning and designing the system, then progressed to the selection of appropriate components, construction of the hardware, software development, and testing of the complete system.

Design Approach: The system designed the way the system would work from capturing the solar energy to wirelessly charging the EV. But pick the components you need, including solar panels, batteries, microcontrollers and sensors. Set up hardware and connected all things like the design. Then we programmed the system to manage the charging process, and send data to the cloud. At last we put the whole system through the paces to see if it was working properly and made appropriate changes.

B. Voltage Drop and Efficiency Calculation

WPT Efficiency Calculation: The wireless power-transfer efficiency was determined from the ratio of the electrical power measured at the receiver to the electrical power supplied to the transmitter. The distance dependent measurements were carried out with the input condition fixed at about 12 V and 1 A.

TABLE I: EFFICIENCY CALCULATION

d (cm)	v_{in} (V)	I_{in} (A)	v_{out} (V)	I_{out} (A)	η (%)
1	12	1	11.0	0.88	91
2	12	1	9.9	0.81	82.5
3	12	1	8.2	0.70	68.3
4	12	1	6.8	0.57	56.6
5	12	1	5.3	0.24	44.1
6	12	1	3.7	0.14	30

C. Coil Design Calculation

The coil design is done using the calculation done various studies [4-9]. It is used to calculate most of the system parameters and are used in the system application.

D. Block Diagram

The solar panel produces electricity and it is controlled and stored in the battery. The wireless charging unit inductively conveys power to the EV and the IoT controller is remotely able to monitor charging, battery condition, faults, and system parameters. The complete energy flow and monitoring process presented in Fig. 2.

E. Flow Chart

The system follows a simple process; Fig. 3 shows the system flow chart.

F. Schematic Diagram

The schematic diagram demonstrates how all the components are connected. It includes:

The solar panel connected to a charge controller and battery. A wireless charging coil connected to the power supply. A microcontroller that reads data from sensors. An IoT module that sends information online. This helped us understand the wiring and build the system correctly. Figure 4 shows the schematic diagram of a solar-powered IoT-based wireless electric vehicle (EV) charging station.

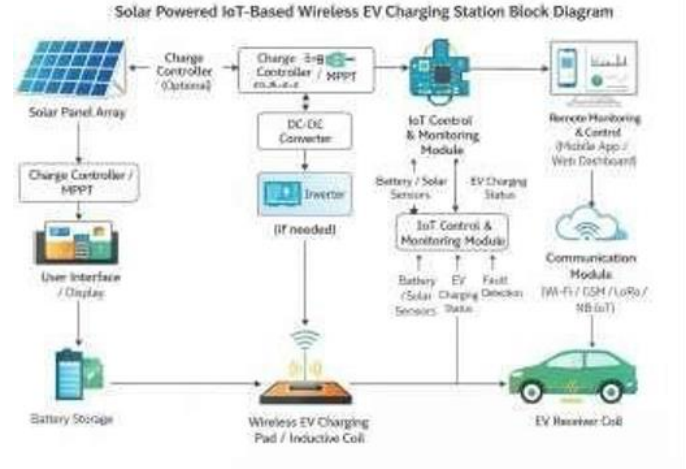


Fig. 2. Block Diagram.

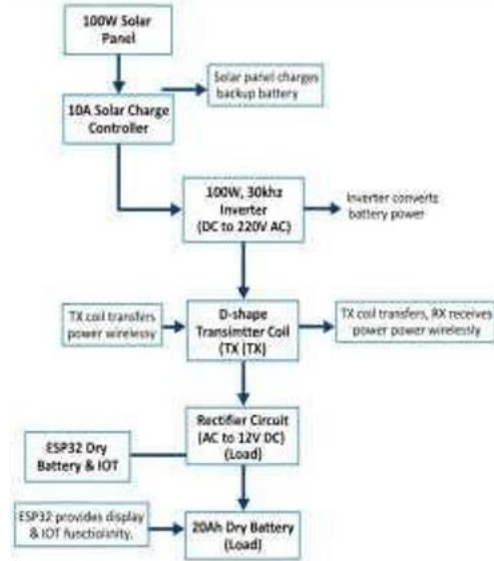


Fig. 3. System Flow Chart.

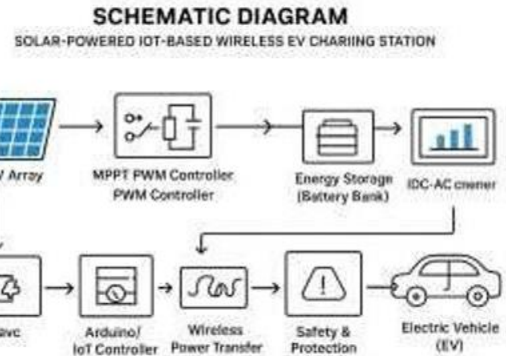


Fig. 4. Schematic Diagram.

G. Components

Table II shows the electrical components and the description of designed system.

TABLE II: ELECTRICAL COMPONENTS

Component	Description / Function
Solar Panel (100 Watt)	Converts sunlight into electrical energy (DC power) for the system.
Battery (Energy Storage Unit)	Stores energy from the solar panel for continuous power supply, even without sunlight.
DC-AC Converter 85 khz	Maintains stable voltage levels required for wireless charging and system electronics.
Wireless Power Transfer (WPT) Module	Enables contactless energy transfer from the transmitter coil to the receiver coil on the EV.
Transmitter Coil	Installed in the charging station; generates an electromagnetic field for wireless charging.
Receiver Coil (in EV)	Mounted on the vehicle to receive power wirelessly from the transmitter coil.
Arduino Microcontroller	Central control unit that manages sensor input, wireless communication, and system automation.
ESP32 Wi-Fi Module	Provides IoT connectivity, sending real-time charging data (voltage, current, status) to the cloud or mobile app.
Voltage and Current Sensors (e.g., INA219, ACS712)	Monitor battery voltage and charging current for power management and safety.
LED Display	Displays real-time charging information such as power, voltage, current, and status.

Experimental Configuration: The coils were placed coaxially for the wireless power-transfer performance test, and the performance was evaluated at fixed distances between the coils of 1, 2, 3, 4, 5, and 6 cm. The DC input to the WPT converter was kept at approximately 12 V and 1 A for an input power of approximately 12 W. The transmitter and receiver coils were made with a diameter of 30cm and the operating frequency was 85kHz. The coils were all D shaped with 12 turns of Litz wire per coil, and ferrite plates were added to increase the concentration of magnetic-flux. The voltage and current were measured at the input and receiver sides to determine the transfer efficiency for each separation distance. The same alignment and electrical input conditions were used for the distance-dependent measurements in order to determine the effect of the distance between coils on WPT performance.

H. Hardware Implementation

The hardware components were placed, and the solar panel was installed in a location where it received an adequate amount of sunlight. The panel is connected to the battery with the help of a charge controller. The wireless charging coil was installed at the location where the car could park above it. The microcontroller was interfaced with all the sensors and other modules, and everything was fixed inside a weatherproof box to ensure safety from outdoor conditions. Hardware setup requires careful wiring,

testing of power connections, and ensuring that everything is safely in place.

Solar Panel: The solar panel is the main source of renewable energy for the wireless charging system. It gathers solar energy and converts the solar energy into electrical energy, which is used to power the MPPT charge controller. The solar panel helps the system to be energy-efficient and environment-friendly, thereby decreasing the dependency on the electrical grid. Figure 5 shows the solar panel, and Table III lists the electrical parameters of the solar panel.



Fig. 5. Solar Panel.

TABLE III: SOLAR PANEL SPECIFICATIONS

Parameters	Specification / Description
Component Name	Solar Panel
Function	Converts solar energy into electrical energy
Energy Source	Sunlight (Renewable Energy)
Output Type	DC (Direct Current) Power
System Role	Primary power source for the wireless EV charging system

Battery: A rechargeable 12 V lead-acid battery with a rated capacity of 65 Ah was used as the energy-storage unit of the prototype. The nominal stored energy will thus be about 780 Wh ($12 \text{ V} \times 65 \text{ Ah}$) in nominal conditions. The battery was used for storing energy in the solar charge controller, and then used the wireless power transfer phase. For experimental testing, the battery was used to deliver a regulated DC power supply to the WPT converter, so that wireless-power transfer tests could be performed with controlled electrical power inputs.

TABLE IV: BATTERY SPECIFICATIONS

Parameters	Specification / Description
Component Name	Battery
Function	Stores electrical energy generated by the solar panel
Energy Storage Type	Rechargeable DC Energy Storage
System Role	Supplies power to the system when solar energy is unavailable
Input Source	Solar Panel through MPPT Charge Controller (Voltage: 12–24 V DC, Current: up to 10 A depending on panel output)
Output Type	DC Power (Voltage: 12–24 V DC, Current: system dependent, e.g., 5–10 A)

Microcontroller and IoT Control Architecture: The main microcontroller/central control unit (CCU) in the proposed charging station was the ESP32 development board. It acquired voltage and current measurements from the sensors, processed the measured data, monitored the charging state and performed the system control logic. The ESP32 also enabled the necessary Wi-Fi connectivity, allowing the measured parameters to be sent to the IoT/cloud platform. The implementation is not using a separate Arduino microcontroller board, but the Arduino compatible development/programming environment where the ESP32 is programmed. For this reason, an additional Arduino controller was not used for the final prototype. This separation helps to avoid any confusion between the system controller and the IoT communication interface.

Charge Controller: Charge Controller is the major component of the Solar Powered IoT Based Wireless EV Charging Station. It makes sure that energy coming from the solar panel is handled properly and made safe to be sent to battery and charging system. Figure 6 Show below charge controller and Table 5 shows the electrical parameters of the description of charge controller.

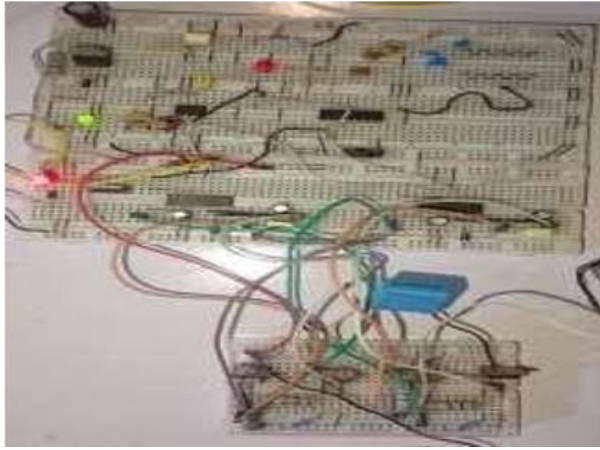


Fig. 6. Controller Charger.

TABLE V: CHARGE CONTROLLER

Parameters	Specification / Description
Component Name	Charge Controller
Function	Regulates and manages the power from the solar panel
Input Source	Solar Panel (Voltage: typically, 12–24 V DC, Current: depends on panel output, e.g., 5–10 A)
Output Connection	Battery and charging system (Voltage: 12–24 V DC, Current: up to 10 A or as per system rating)
Power Type	DC Power Regulation
System Role	Controls charging, prevents overcharging, and ensures stable voltage & current supply
Protection Features	Overcharge protection, voltage regulation, overcurrent protection, and safe energy management
System Benefit	Improves battery life, ensures stable operation, and protects voltage & current for efficient EV charging

Microcontroller (ESP32): The “brain” of the system. Now, let us understand the role and operational details of the microcontroller (ESP32) in the solar-powered IoT-based wireless EV charging station project. Figure 7 shows the microcontroller, and Table VI lists the electrical parameters of the Arduino description.



Fig. 7. Microcontroller (Arduino ESP32).

TABLE VI: MICROCONTROLLER (ESP32)

Parameters	Specification / Description
Component Name	Microcontroller (Arduino / ESP32)
Function	Acts as the “brain” of the system; controls and monitors all Operations
Input Source	Sensors, IoT modules, user commands
Output Control	Wireless charging coils, indicators, communication modules
System Role	- Processes sensor data (voltage, current, battery level) - Controls charging process - Manages IoT communication and remote Monitoring
Key Features	- Programmable logic for automation - Supports Wi-Fi/Bluetooth (ESP32) for IoT - Interfaces with sensors and actuators
System Benefit	Enables smart control, real-time monitoring, and automation for efficient EV charging

Ferrite plates: Ferrite plates play a crucial role in a wireless EV charging system, especially in the transmitter and receiver coils. Figure 8 shows the ferrite plates (Transmission and receiver coil).



Fig. 8. Ferrite plates.

Voltage and Current Sensors (INA219, ACS712): Voltage and current sensors are key components for monitoring and managing the flow of energy in a solar-powered wireless EV charging station. They provide real-time measurements that are used by the microcontroller to control charging and ensure safety.

INA219 sensor: A high side voltage & current sensor Esp32 pins connected to the microcontroller: - Communicates through I²C

protocol with ESP32 Measures the voltage and current at the same time. In addition, the electrical control module will provide the following features: - ideal for accurate monitoring of battery charging and power consumption.

ACS712 sensor (Hall effect based current sensor): The analog output is proportional to the current flowing in the charging circuit, and can be defined as: - Measures AC or DC current passing through the charging circuit Real-time current monitoring and overcurrent protection.

I. Software Implementation

Software implementation plays an important role in enabling intelligent monitoring, control, and automation of solar-powered wireless EV charging stations. The system includes a microcontroller-based program and IoT connectivity to coordinate the system actions and monitor the performance of the system.

The microcontroller was programmed to read the data from the voltage and current sensors, which were connected to the charging system. These sensors continuously measured important electrical parameters, such as the input voltage, output voltage, charging current, and battery level. The collected information was processed by the microcontroller and used to control the functions of the system, such as starting or stopping the charging process and maintaining safe operating conditions. The software also incorporates IoT communication so that the system can communicate with a cloud platform by sending real-time data using a Wi-Fi module. This allows remote monitoring of the charging station via a web or mobile-based dashboard for the user. The dashboard is provided for important data on the system like charging status, solar energy generation, battery level and energy consumption. In addition to monitoring, the software offers features for automation and protection. The program ensures that the battery is charged safely so that healthier voltage and current levels are maintained, and that the battery is not overcharged or discharged in excess. It can also trigger alerts in case of any abnormal condition, such as low battery voltage or high current.

When it comes to the overall system, the software implementation enhances system efficiency, reliability, and user convenience by implementing real-time monitoring, remote control, data logging, and automatic system management using IoT technology. Figure 9 shows the flow chart of the design and development of a solar-powered IoT-based wireless electric vehicle (EV) charging station.

IV. RESULTS AND DISCUSSION

A. Wireless Power Transfer Systems that are Stable

The wireless power transfer system successfully transferred electrical energy from the transmission coil to the reception coil through inductive coupling. When an alternating current was passed through the transmitter coil, a magnetic field was produced, which caused an induction of voltage in the receiver coil placed within close proximity. The system demonstrated stable energy transfer at short distances, especially between 1 and 3 cm, where the highest efficiency levels were observed. As the space between the coils increased, the output voltage and current gradually decreased, which is expected in inductive wireless charging systems.

Practical Implications of Coil Separation: The measured WPT efficiency decreases substantially as the separation between the transmitter and receiver coils increases. The efficiency decreases from 91% at 1 cm to 82.5% at 2 cm, 68.3% at 3 cm, 56.6% at 4 cm, 44.1% at 5 cm, and 30% at 6 cm. This behaviour suggests that the prototype is quite sensitive to the air gap between the coils and that the coils need to be lined up at least reasonably close to each other for use. To sum up, this means that the charging time will increase significantly at higher separation distances and the charging power to the EV battery will decrease as well.

In a stationary application where the charger is used for parking, the observed limitation may be controlled by positioning the charger (transmitter coil) at a controlled parking position and keeping the vertical distance between the transmitter and receiver coil small and constant. The relatively low efficiency at the larger gaps, however, makes the present prototype unsuitable for applications where the ground clearance must be large, the coil misalignment must be large, or dynamic wireless charging is desired. The coil geometry, resonant compensation, magnetic-flux guidance, alignment tolerance, and power-electronic conversion stages should thus be optimized in the future, as well as higher conversion stages.

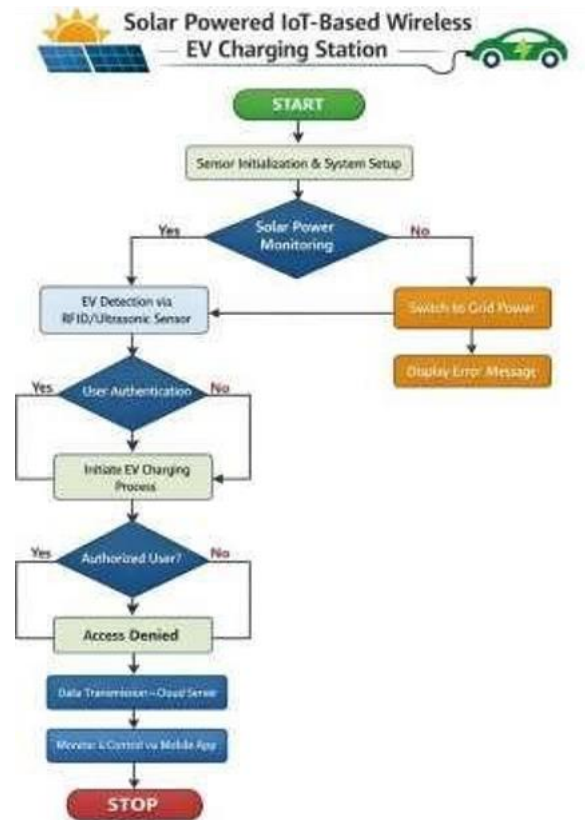


Fig. 9: Software Flow Graph.

B. Efficient Utilization of Solar Energy

The solar panel successfully converted sunlight into electrical energy and provided power to the charging system through the charge controller. The MPPT charge controller ensured that the solar panel operated at its maximum power point, and thus,

energy harvesting was efficient. The generated energy was stored in the battery and later used to power the wireless charging circuit. This confirms that the system can be run off renewable solar energy and relieves dependence on conventional grid electricity.

C. Real Time Monitoring using IoT Dashboard

The integration of IoT technology enabled continuous monitoring of the system parameters, such as voltage, current, battery level, and charging status. The microcontroller was used to collect data from the sensors and send them to a cloud-based IoT platform. Through a web or mobile dashboard, users could view the system performance in real-time, analyze energy consumption, and remotely monitor the charging process. This feature helps to improve system transparency and to detect problems in operation quickly.

D. Proper Charging and Protection of Batteries

The charge controller was able to successfully regulate the way that the battery was charged by controlling the voltage and current levels. This prevented overcharging, deep discharge, and voltage fluctuations. This ensured safe battery operation and increased battery life. During testing, the battery exhibited stable voltage levels and continuously provided energy to the wireless charging system under low solar energy input.

E. Reliable Data Transfer to the Cloud

The microcontroller that was connected to Wi-Fi, could send the data from the sensors to the cloud server. The data transmission was stable even in the testing phase, with the possibility of updating the system in real-time and storing historical data. Such reliable interaction between the hardware elements and IoT platform makes it possible to monitor and control systems remotely.

F. Overall System Performance

The test outcomes indicate that the wireless EV charging system powered by solar energy is capable of operating without relying on the electrical grid to an extent. Solar power generation, wireless power transmission, and IoT monitoring collectively provide an eco-friendly and intelligent charging solution for EVs, particularly in off-grid and remote areas.

G. User Interface

The developed system consists of an easy-to-use interface for users and operators to monitor and control the EV charging process easily using an IoT dashboard. The interface is designed to provide clear information about the performance of the system as well as remote operation.

Real-Time Monitoring: The dashboard displays near real-time information regarding electrical parameters, such as voltage, current, and battery level. These values are continuously collected using sensors and transferred by the microcontroller to the Internet of Things (IoT) platform. This allows users to observe the performance and charging conditions of the system at any time.

Charging Status Display: The interface provides information about the current charging status whether the EV is charging, fully charged, or disconnected. This helps users to determine the charging progress and manage their charging schedule efficiently.

Energy Statistics and Generation: The system also displays the data related to solar energy generation and energy consumption. Users can view the amount of power generated by the solar panel and the amount of power stored in the battery and used by the charging process. This feature can be useful to evaluate the efficiency of the system and the energy consumption of the system.

Remote Control: From the IoT dashboard, users can control the charging process, either by starting it or stopping it, remotely. The remote-control feature simplifies the charging process and allows the charging station's operator to control it remotely, without having to be at the site.

Fault Alert Notifications: A fault detection and notification system is integrated in the interface. In case of any abnormal condition like low battery voltage, abnormal current or any malfunction of the system, the dashboard will alert the user. This helps in quick identification of problems, and safe operation of the system is ensured (see Fig. 10 and Fig. 11).

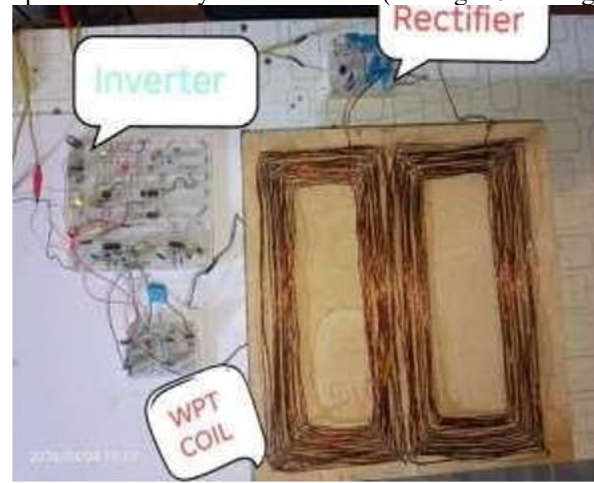


Fig. 10. Circuit Overview



Fig. 11. Dashboard.

V. CONCLUSION

This Solar-Powered IoT-Based Wireless Electric Vehicle (EV) Charging Station system was designed, developed, and ultimately tested, as a sustainable and intelligent electric vehicle (EV) charging solution. The system uses solar photovoltaic energy generation, inductive coupling wireless power transfer,

battery energy storage, and IoT-based monitoring and control. The overall goal of the project was to reduce the reliance to conventional charging infrastructure based on the grid and promote the use of renewable energy for the electric vehicle charge. During the developing phase of the system, it was designed with more care, with some essential components such as solar panel, charge controller, rechargeable battery, microcontroller, wireless receiver and transmitter coils, sensors, and IoT communication modules. The solar panel was used to convert sunlight into electricity, which was controlled by the charge controller and stored in the battery for continuous use. The stored energy was then fed to the wireless charging circuit, where the power was transferred from the transmitter coil to the receiver coil by inductive coupling. Experimental testing proved that the wireless charging system was able to efficiently transfer energy over short distances. The results indicated that the output voltage and efficiency gradually decreased with increasing distance between the transmitter and receiver coils. However, stable and reliable power transfer was achieved within a small operating range, which is applicable for wireless EV charging applications, such as parking-based charging systems.

The experimental results also point out that a practical drawback of the prototype is that the efficiency of the WPT drops from 91% at a separation of 1cm to 30% at 6cm. This makes it more suitable for controlled stationary charging setups where the transmitter and receiver coils can be kept closer together and in better alignment. Further optimization of the coil structure, resonant compensation, magnetic coupling, and power-conversion circuit would be needed for an increase in allowable air gap. The integration of IoT technology played an important role in improving the functionality of the system. The microcontroller gathered data from the voltage sensor and the current sensor, and sent the data to a cloud-based platform. Through the IoT dashboard, users were able to monitor, in real-time, system parameters, such as voltage, current, battery level, solar energy generation, and charging status. The system also provided remote control and fault alert notification, enhancing the reliability and convenience of the system. The other important achievement of the prototype is that it uses the solar energy properly. By using solar power as a primary source of energy, the system reduces the requirement for using fossil fuel-based electricity and is part of environmentally friendly energy solutions. This makes the proposed charging station very viable in remote areas, rural areas and areas with limited or non-existent grid connectivity.

In conclusion, the developed system demonstrates the viability of this integration of solar energy, wireless charging, and IoT monitoring for creating a smart and sustainable EV charging infrastructure. The prototype was successful in achieving the goals, but there are opportunities for improvement. Future research could explore wireless power transfer efficiency, expanding the system for greater power and EV charging capability, implementing advanced control methods, and implementing AI-based energy management systems for further optimization.

VI. FUTURE PROSPECTS

Increasing Wireless Power Transfer Efficiency: Improve the efficiency of wireless charging by designing improved coils, distance between the coils and resorting to better resonant circuits. This will minimize energy wastage and enhance the performance of charging.

Installation of AI-Based Energy Management Systems: The data available in the systems can be analyzed using artificial intelligence, such as the production of solar energy and the demand for charging. It is capable of automatic control of energy distribution as well as prediction of solar power availability and charging schedule optimization.

Formulating Greater Power load Charging Capacity: Next-generation systems can be developed to manage greater voltage levels and currents, thereby enabling electric vehicles to be charged more rapidly and easily.

Instant Automatic Vehicle Detection: The sensors can include RFID or infrared, and once a vehicle enters a charging station, the process will automatically begin.

Additional IoT Support to Smart Grid Interface: To track energy consumption, remotely control the charging process and optimize the consumption of electricity according to the demand of the grid, the charging station may be connected to a smart grid.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest to report regarding the present study.

AUTHOR CONTRIBUTIONS

Conceptualization, S.S.A., A.A., W.A., and M.I.A.; methodology, S.S.A. and M.Z.; software, S.S.A., and W.A.; validation, M.Z.; formal analysis, S.S.A., A.A., and W.A.; investigation, S.S.A. and M.Z.; resources, M.Z.; data curation, A.A.; writing—original draft preparation, S.S.A., A.A., W.A., and M.I.A.; writing—review and editing, M.Z.; supervision, M.Z.; project administration, W.A. and A.A.

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Data is available on reasonable request.

CONSENT FOR PUBLICATION

All authors have read and approved the final version of the manuscript and consent to its publication.

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

For preparing this manuscript, the authors have only made use of generative artificial intelligence systems to enhance language proficiency, grammar, and readability.

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