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Design and Implementation of a Hybrid Solar–Grid Based Portable EV Charging Station

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ABSTRACT: This study presents the design and development of a portable Electric Vehicle Charging Station (EVCS) that ensures convenient and secure charging of electric vehicles. The proposed prototype integrates both the conventional 220V AC grid supply and renewable energy from solar panels, with automatic switching between the two sources. The system is built on an Arduino microcontroller platform, incorporating a GPS module, Bluetooth interface, and relays to provide safe control and continuous monitoring. Experimental validation was carried out using a small-scale 12V, 10Ah battery, where results showed a charging time of approximately 1 hour 15 minutes with solar energy and 2 hours 30 minutes using the grid supply. The IoT-based interface of the device allows user authentication, monitoring of energy consumption via a digital energy meter, and secure recording of transaction data. Therefore, the EVCS prototype offers an eco-friendly, efficient, and user-friendly charging solution, representing an important step toward the transition to sustainable transportation systems.

KEY WORDS: electric vehicles, portable charging station, Arduino Uno, Bluetooth HC-05, NEO-6M GPS, solar panels, relay, digital energy meter.

I. INTRODUCTION

A universal charging station is designed to power vehicles produced by different manufacturers, each equipped with batteries of diverse capacities and charging requirements. Such a system enhances the reliability of electric mobility and stimulates demand for EVs. The underlying principle is straightforward: by adjusting current and voltage levels, the charger delivers the precise amount of power necessary for rapid charging, while the controllers ensure stable and regulated energy transfer.

The prototype presented here represents a reduced-scale version of a real installation but mirrors its operational functions. Continuous monitoring is incorporated into the design, guaranteeing security and eliminating the risk of unauthorized electricity usage. As an IoT-based programmable system, it provides a safe interface that allows users to connect and charge whenever required.

Solar power, being renewable, inexhaustible, and environmentally clean, offers a sustainable solution for energy demand. Its efficiency and eco-friendly nature make it an ideal resource to reduce the negative impact of pollution. In the context of growing concerns about climate change, widespread adoption of renewable energy-driven transportation has become imperative, although mass deployment remains a significant challenge.

One effective response to this challenge is to utilize decentralized solar energy for charging electric vehicles, thereby achieving near zero emissions and supporting a rapid transition toward greener practices.

Advances in fast-charging technology and improved performance are expected to drive higher adoption of EVs. Nonetheless, consumer hesitation persists, as many worry about the possibility of depleting the battery mid-journey. This uncertainty often leads individuals to choose conventional vehicles despite environmental concerns, as they prioritize convenience and assurance[2-5].

Between 2000 and 2024, the global automotive sector consistently stood among the world's largest industries. Annually, millions of passenger and commercial vehicles were produced and distributed across markets. Over these years, the industry not only fulfilled local demands but also catered to international markets, solidifying its strategic role in global manufacturing. While 2019 marked strong performance in commercial vehicle production, the pandemic in 2020 caused a temporary setback. However, from 2021 through 2024, the industry rebounded, with production and sales recovering to reaffirm the essential role of transportation in the world economy.

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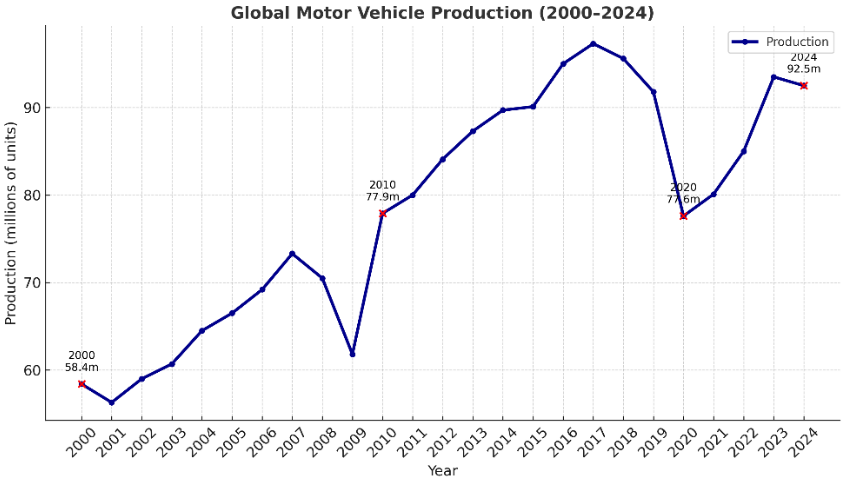

Figure1: Global Motor Vehicle Production (2000–2024)

This chart shows how much carbon dioxide is produced in a given year.
- These figures are based on 'production' emissions (i.e., emissions from the burning of fossil fuels within a country's borders).
- These figures look specifically at carbon dioxide emissions – not total greenhouse gas emissions.
- Annual emissions can be primarily influenced by population size – we present the per capita figures above.

The prototype listed in this report is a portable charging station that is present more frequently and at regular intervals on the roads. This device is placed at the poles of the street lamps, taking power from them and running it through a parallel connection and charging the vehicle plugged in.
The device is an IOT based programmable, secure interface providing customers with a plugin for charge when in need[1].

II.RELATED WORK

Recent studies on electric vehicle charging highlight the integration of renewable energy sources, particularly solar power, as a key solution to reduce emissions and improve sustainability. Hybrid systems that combine solar panels with grid electricity have been shown to enhance reliability and efficiency.
Researchers have also explored IoT-based technologies for smart monitoring and control, enabling secure user authentication, energy tracking, and protection against electricity theft. In addition, several works emphasize fast-charging strategies, where voltage and current are dynamically regulated to reduce charging time.
Most prototypes in the literature employ scaled-down models with small-capacity batteries to validate system performance before full-scale deployment. These efforts collectively underline the need for hybrid, intelligent, and portable charging systems, which form the basis of the present study[4-5].

III. SIGNIFICANCE OF THE SYSTEM

The proposed hybrid solar–grid based EV charging system carries significant importance in the context of sustainable transportation and energy efficiency. By integrating renewable solar energy with the conventional power grid, the system ensures continuous availability of charging facilities while simultaneously reducing dependency on fossil fuels and lowering carbon emissions.
The inclusion of IoT-enabled components such as GPS, Bluetooth, and digital energy meters enhances the security, transparency, and user accessibility of the charging process. This makes the system not only technologically reliable but also user-friendly, preventing electricity theft and ensuring accurate monitoring of energy consumption.
Furthermore, the portability of the prototype allows for wider deployment in urban and rural environments, particularly in areas where permanent infrastructure is not feasible. By supporting both conventional and renewable energy sources, the system represents a practical and scalable solution that contributes to the global transition toward eco-friendly mobility[6-8].

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IV. METHODOLOGY

The following components are used in the EVCS set up in a procedural circuit and respective pin diagram. The Arduino, the primary control for the prototype, is explicitly programmed, and it controls the HC05, NEO 6M, and the relay.

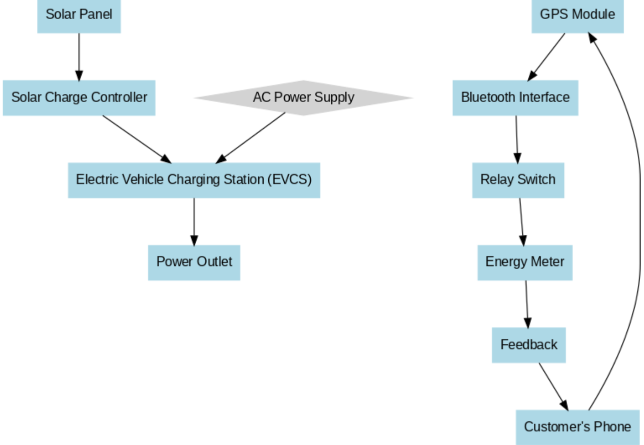

Figure2: Block Diagram of Electric Vehicle Charging Station (EVCS) Working Process

The schematic representation demonstrates the step-by-step operational sequence of the Electric Vehicle Charging Station (EVCS) together with its functional components. In this setup, two relays play a critical role by automatically regulating the source of power supply. Depending on the availability of resources, the relays intelligently switch between the conventional AC grid connection and the solar energy input. This automated switching mechanism not only ensures continuous energy delivery to the charging station but also optimizes the utilization of renewable energy when sunlight is available. Such a dual-source integration increases the system's efficiency, reliability, and sustainability, while minimizing dependence on a single energy source.

Arduino Uno. The Arduino Uno is an open-source microcontroller platform built around the Microchip ATmega328P. Originally developed by Arduino, this board is widely applied in numerous electronic systems. Its key features include both digital and analog I/O pins, which allow seamless interfacing with sensors, modules, and expansion boards (shields). Out of its 14 digital I/O pins, six can provide PWM output, and it also has 6 analog pins for signal acquisition. The Arduino Uno can be programmed through the Arduino IDE (Integrated Development Environment), making it highly versatile and user-friendly for prototyping[8-9].

Bluetooth Module (HC-05). The HC-05 Bluetooth module is designed for establishing wireless serial communication based on the Serial Port Protocol (SPP). It can operate in both Master and Slave modes, making it highly adaptable for different communication needs. This module is fully compliant with Bluetooth V2.0+EDR standards, supporting data transfer rates up to 3 Mbps. Internally, it integrates a complete 2.4 GHz transceiver and baseband processor, ensuring reliable wireless connectivity within the EVCS system.

Relay. A relay is an electromechanical switch that operates by controlling the flow of current through its contact terminals. Relays may be manufactured in several configurations, such as normally open (NO), normally closed (NC), or a combination of both. They can be easily activated or deactivated, allowing current to either flow or be interrupted. In the EVCS design, relays are controlled by a low voltage (5V) signal provided by Arduino pins, making them an effective solution for switching between power sources and safeguarding the battery from overload.

NEO-6M GPS Module. The NEO-6M GPS module is a satellite navigation device capable of receiving signals from up to 24 GNSS satellites orbiting the Earth. It calculates and transmits the device's geographic coordinates in terms of latitude and longitude. Within the EVCS setup, this module is essential for accurately locating charging stations and providing location-based services to users.

Solar Panel. A solar panel consists of an array of photovoltaic (PV) cells assembled within a protective frame. These cells directly convert sunlight into electrical energy, which can then be stored in batteries for later use. Solar panels provide a clean, renewable source of energy, making them an environmentally sustainable solution for powering EVCS infrastructure.

Solar Charge Controller. The solar charge controller regulates the flow of voltage and current between the solar panel and the battery. It incorporates protective components such as n-channel MOSFETs and Zener diodes to prevent damage. For example, a 10V Zener diode prevents undervoltage conditions by sending positive feedback to activate the relay,

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while a 15V Zener diode protects against overvoltage by sending negative feedback to shut off the relay. An additional MOSFET ensures that the battery is protected from overcharging by disabling the charging circuit when necessary.

Digital Energy Meter. The digital energy meter continuously measures instantaneous voltage and current, multiplies them to calculate real-time electrical power, and integrates this value over time to determine the total energy consumed during charging. In the EVCS system, this component plays a crucial role in monitoring power usage and recording user consumption data for billing and analysis.

The GPS module, Bluetooth module, and the relay are all attached to the Arduino in a specific way. The main objective of this model is to obstruct and retract the power flow using a relay with the help of a Bluetooth interface.

The prototype is designed to be placed at the bottom of street lamps. The power lines that flow at the street lamps carry 220v, exactly what is received at our houses. Using this concept, the charging of EVs will take place outside with a voltage of 220v. Additionally, a solar panel is added, which is used to extract the solar energy and convert it into usable electricity. The panel has its respective solar charge controller, which regulates the voltage flow into the battery.

The vehicle which is to be charged has been scaled down and assumed to be a battery of 12v and 10Ah. The solar charge controller extracts the power from the Sun's solar radiation, steps down the voltage, and supplies it to the battery accordingly.

The EVCS contains two relays that switch automatically in delivering power. A light sensor is adapted to detect the presence of sunlight. Relay 1 is turned off in the absence of the Sun, and Relay 2 is active, usable for power delivery.

During the day, in bright sunlight, the user can use either solar energy or conventional electricity from the grid. The 2 Relays which are present can be activated based on the requirement. The EVCS contains an Arduino connected to the GPS module, Relays, and the Bluetooth module. The two possible ways are explained as follows.

Case 1: Solar Charging - Relay 1

In the presence of sunlight, Relay 1 is active and can be turned on or off. The solar radiations are converted into electricity and pass through the solar charge controller. The solar charge controller is a voltage and current regulator to keep batteries from overcharging and overheating. It regulates the current and voltage coming from the solar panels and going to the battery safeguarding it by preventing it from over-voltage, low voltage, and back current. Relay 1 is turned on, and the charge starts to flow from the Solar panel into the battery. At this time, Relay 2 is inactive.

Case 2: Electric grid charging - Relay 2

The electricity from the street pole directly enters Relay 2 (active Relay), and Relay 1 is inactive. The user plugs in his car for charging using the home adapter, and the electricity from the 220v line passes through and charges the vehicle. When the charging sequence begins, it is ensured that the power is supplied from one source only. The responsible relay is the only one that is specifically turned on. Both the relays cannot be on at the same time.

Instance:

An electric vehicle is low on battery; the driver searches for the nearest charging station on his phone. The charging stations are provided with a unique location tag and are located through GPS. The NEO 6M GPS module actively tracks 24-30 satellites and sends the coordinates to the phone. The coordinates are then decrypted, and the exact location is shown on the map. The vehicle halts at the desired parking space and locates the EVCS. The user can choose between Solar charging (provided the relay is active in the presence of solar radiations) or electric grid charging. The charging wire is plugged into the outlet of the EVCS, or in the case of solar charging, the charging wire is connected to the inlet of the vehicle. The plugged-in socket has a 220v line which has been drawn from the street lamp.

The consumer authenticates as a registered owner of an electric vehicle with the stored database. The credentials are entered, and access is granted. Bluetooth is turned on and an interface is created linked to the respective EVCS, enabling the charge to flow. Engaging and disengaging the power supply is done through the mobile application. Once engaged, the Arduino recognises the user as a trusted source and sends information to the relay. The relay then closes the circuit, providing power flow. A digital energy meter is placed, and the power consumed is monitored consistently. The consumer's information is recorded and stored in the server, and the number of units consumed along with the per-unit cost is calculated. Once the charging is complete, the circuit is disengaged, and the relay turns off the current flow. The energy meter tracks the power consumption and stores the data, which is later sent to the consumer's phone. After disengaging the supply or completing the charge, the payment gateway is opened, and the transaction is made.

This completes the entire process of charging an EV. The charging of the EVs is made easy, hassle-free, and secure. It also ensures that the electricity is not stolen and solely used to charge the respective EVs [10-13].

V. EXPERIMENTAL RESULTS AND DISCUSSION

The charging system consists of a photovoltaic (PV) source with a nominal output of 18V**, a** 12V, 10Ah lead-acid (or Li-Ion) battery**,** and an auxiliary220V, 50Hz AC grid**.** The solar charge controller adjusts the incoming voltage from the PV module to align with the required charging profile of the battery.

The instantaneous power transferred to the battery can be expressed as:

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$$P(t) = V_b(t) \cdot I_b(t)$$

where $V_b(t)$ is the time-varying terminal voltage of the battery, and $I_b(t)$ is the charging current. Unlike the simplified relation $P = V \times I$,, the current here is a nonlinear function of the state-of-charge (SOC) of the battery:

$$I_b(t) = \frac{V_{in}(t) - V_b(t)}{R_{eq} + R_{int}(SOC)}$$

Here:

- $V_{in}(t)$ – the regulated input voltage (12V after conversion from 18V PV source),
- R_{eq} – equivalent resistance of the charging circuit,
- $R_{int}(SOC)$ – internal resistance of the battery, which varies with SOC.

The battery's stored energy at time ttt can be described as:

$$E(t) = \int_0^t P(\tau)d\tau = \int_0^t V_b(\tau) \cdot I_b(\tau)d\tau$$

The SOC dynamics are modeled as:

$$SOC(t) = SOC(0) + \frac{1}{C_{nom}} \int_0^t I_b(\tau)d\tau$$

where $C_{nom} = 10$Ah is the nominal battery capacity

For solar charging with $V_{in} \approx 18V$ stepped down to 12V and current regulated around **10A**, the effective average charging power is:

$$P_{solar} \approx 120W$$

Thus, the theoretical charging duration to reach 80% SOC is:

$$T_{80\%}^{AC} = \frac{0.8 \cdot C_{nom} \cdot V_b}{P_{solar}} \approx 1\ hour$$

For AC grid charging, the adapter provides $V_{out} = 12V\ and\ I = 5A$, giving:

$$P_{AC} = 60W$$

Hence, the time to reach 80% SOC is approximately:

$$T_{80\%}^{AC} = \frac{0.8 \cdot C_{nom} \cdot V_b}{P_{AC}} \approx 2\ hour$$

The total theoretical full-charge times can be similarly derived: 1.25 hours for solar and 2.5 hours for AC grid.

During experimental validation, the Arduino-based EVCS prototype was connected to a single-phase 220V AC line, with the control unit powered by an auxiliary 9V source. The relay in its idle state acts as a circuit breaker:

$I_{out}(t) = 0$,when relay is OFF

The system is activated through a Bluetooth-enabled Android application, which provides secure authentication and control signals. Once the relay is switched ON, the Arduino processes the command:

$$Relay_{state}(t) = f_{ctrl}(Bluetooth_{cmd}, SOC, V_{in})$$

and current begins to flow into the battery. The energy meter simultaneously records instantaneous power and integrates it over time to provide total energy consumption.

V. CONCLUSION AND FUTURE WORK

The implemented setup demonstrated efficient and error-free operation, with the battery charging process successfully completed and both the charging duration and energy consumption accurately recorded. Continuous monitoring throughout the procedure ensured that no malfunctions or unnecessary power losses occurred. The system operated without noticeable fluctuations, as the voltage was consistently stabilized and regulated by integrated circuits and the microcontroller, both of which played a crucial role in maintaining steady voltage and current flow.

To further enhance system performance, fast-charging capability from both energy sources — solar and 220V AC grid — should be optimized in order to reduce the overall charging duration. The prototype developed for this study was a scaled-down version, and the experimental validation was carried out using a compact 12V, 10Ah Li-Ion battery. Under these test conditions, the measured charging times were approximately 2 hours and 30 minutes using the AC adapter and 1 hour and 15 minutes using solar energy.

At present, the device operates with a limited sequence of programmed instructions, delivering power via a relay-controlled switching circuit. Importantly, the switching process (ON/OFF) is performed securely, following established communication protocols between the smartphone application and the EVCS prototype, thereby ensuring safe and reliable functionality[14-15].

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