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Dual-Source Solar and Piezoelectric EV Charging Station: A Novel Hardware Solution

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Abstract: *Electric Vehicles (EVs) are pivotal in reducing greenhouse gas emissions and diminishing reliance on fossil fuels. However, conventional EV charging stations often suffer from energy intermittency, particularly during nighttime or under variable weather conditions. This research presents an advanced dual-source EV charging station that integrates solar and piezoelectric energy harvesting to deliver continuous, sustainable energy for EV charging. The system features bifacial solar panels with dual-axis tracking, maximizing energy capture by harnessing direct and reflected sunlight. Complementing this, piezoelectric tiles, strategically installed in high-traffic zones like parking lots and access roads, generate electricity from mechanical vibrations induced by vehicular movements, ensuring consistent power generation irrespective of environmental conditions. The integration of advanced power management components, including multi-input DC-DC converters, solid-state batteries, and supercapacitors, optimizes energy storage, supports rapid charging, and guarantees stable power delivery. Achieving over 90% overall energy efficiency and reducing grid dependency by up to 80%, the dual-source system ensures 24/7 operation while significantly enhancing energy availability. This eco-friendly architecture promotes reduced carbon emissions, robust reliability, and enhanced user convenience, offering a transformative solution for sustainable EV charging infrastructure.*

Keywords: *Electric Vehicles (EVs), Dual-Source Charging Station, Renewable Energy Integration, Piezoelectric Energy Harvesting, Sustainable Infrastructure*

I. INTRODUCTION

The electrification of transportation is pivotal to achieving global sustainability goals, reducing carbon emissions, and addressing the challenges of climate change. Electric Vehicles (EVs) have emerged as a clean alternative to traditional internal combustion engine vehicles, offering significant reductions in greenhouse gas emissions and reliance on fossil fuels [1]. However, the widespread adoption of EVs brings a critical challenge: the need for reliable, efficient, and sustainable charging infrastructure. The availability of such infrastructure is crucial for supporting the growing EV fleet and ensuring a seamless user experience [2].

Traditional EV charging stations typically rely on grid or solar energy to charge electric vehicles. While solar-powered stations offer an environmentally friendly solution, they are not without limitations [3]. Solar energy generation is inherently intermittent—its availability is directly influenced by weather conditions and time of day. For instance, solar panels produce little to no energy during cloudy days or at night, making it difficult to guarantee a continuous supply of power. This limitation poses a significant challenge, especially in areas where solar radiation is inconsistent or for regions with long periods of cloud cover or darkness [4].

In contrast, piezoelectric energy harvesting presents an innovative solution to this problem. Piezoelectric systems have the unique ability to convert mechanical energy, such as vibrations or pressure, into electrical energy. This technology has been explored extensively for small-scale applications like powering wearable devices or sensor networks [5]. However, its potential for large-scale energy generation, especially in the context of EV charging, remains largely untapped.

The ability to capture energy from mechanical vibrations or movements—such as those generated by vehicles driving over roads or parking in high-traffic areas—offers a consistent and renewable power source. When implemented in high-traffic zones, piezoelectric energy harvesters can continuously generate power, even during overcast weather or nighttime hours, ensuring a reliable energy source for EV charging stations [6]. This research proposes a novel dual-source EV charging station that integrates both solar and piezoelectric energy harvesting technologies. By combining these two renewable energy sources, the system capitalizes on the complementary strengths of each. Solar power provides energy during the day, while piezoelectric harvesters generate electricity from vehicle movements, ensuring continuous power availability regardless of weather conditions or time of day.

This dual-source approach addresses the key limitation of traditional solar-powered charging stations—intermittency—by providing energy redundancy and ensuring a more stable and reliable energy supply for EV users.

The proposed charging station integrates high-efficiency bifacial solar panels, which can capture sunlight from both the front and rear surfaces of the panel, increasing energy generation efficiency. Alongside this, piezoelectric energy harvester embedded in high-traffic areas, such as parking lots and access roads, convert mechanical stress into electricity. The energy generated from both sources is managed through an advanced power management unit (PMU) that ensures seamless integration of the two energy inputs. This system also incorporates energy storage solutions such as solid-state batteries and supercapacitors, which provide efficient energy storage and fast power delivery to EVs.

This dual-source charging station represents a sustainable and efficient solution for the growing demand for EV charging infrastructure. By integrating two complementary renewable energy sources, the system not only addresses the challenges of energy intermittency and availability but also provides a scalable solution with the potential for widespread deployment. This research aims to demonstrate the feasibility and advantages of combining solar and piezoelectric energy for EV charging, offering insights into the design and integration of such a system, as well as its environmental, economic, and practical benefits.

A. Organization of the Paper

The paper is organized into well-defined sections, starting with Section 2, which provides a comprehensive Literature Review examining existing studies on solar-powered EV charging, piezoelectric energy harvesting, and their integration potential. Section 3, Proposed System, elaborates on the architecture, including bifacial solar panels, piezoelectric harvesters, energy storage solutions, and power management components. Section 4, Methodology, outlines the design, installation, and optimization process for the system's components. Section 5, Results and Discussion, presents the key findings, including energy efficiency, component durability, energy contributions, and grid dependency reduction, supported by visual data representations. Section 6, Conclusion, highlights the system's effectiveness in providing sustainable EV charging, while Section 7, Future Work, discusses scalability, material advancements, and AI integration for further optimization. Finally, the References section lists all the works cited in this research.

II. LITERATURE REVIEW

The development of Electric Vehicle (EV) charging infrastructure has become a priority globally, as the adoption of EVs continues to grow. Ensuring a reliable, sustainable, and cost-effective energy supply for charging stations is essential for meeting the increasing demand. As such, various energy sources have been explored to power these stations, with solar energy being one of the most popular renewable sources. However, while solar-powered EV charging stations offer a clean and renewable solution, they face inherent limitations primarily related to the intermittency of sunlight [7]. Additionally, piezoelectric energy harvesting, which has primarily been explored for small-scale applications, has significant potential for large-scale energy generation but has not yet been fully integrated into mainstream EV charging infrastructure [8]. This section reviews the existing literature on solar-powered charging stations, and piezoelectric energy systems, and how integrating these technologies could offer a more reliable and sustainable solution for EV charging.

A. Solar-Powered EV Charging Stations

Solar energy is one of the most widely used renewable sources for powering EV charging stations. Photovoltaic (PV) systems have been extensively researched and deployed in EV charging applications due to their ability to generate electricity directly from sunlight. Studies have shown that solar-powered EV charging stations can significantly reduce the carbon footprint associated with conventional grid-powered stations. Mohamed et al. explored the design and realization of solar-powered EV charging stations, highlighting the environmental benefits and cost-effectiveness of integrating photovoltaic (PV) systems into EV infrastructure. Their study demonstrated that such stations could contribute to green energy goals by reducing dependency on the grid and lowering CO₂ emissions [9].

However, the major limitation of solar power is its dependence on weather conditions and time of day. While solar energy is abundant in sunny regions, its availability significantly decreases during cloudy weather or at night, leading to gaps in energy availability for EV charging. To address these limitations, various enhancements have been proposed, such as integrating solar energy with energy storage systems (e.g., batteries and supercapacitors) to store excess energy for use during periods of low sunlight. While these solutions improve energy availability, they still do not eliminate the issue of solar intermittency. Kumar et al. proposed a hybrid solar-based charging station, integrating energy storage systems to bridge the gap created by solar intermittency.

However, this approach still depends on the availability of sunlight, making it less effective during certain weather conditions or times of day [10].

B. Piezoelectric Energy Harvesting

Piezoelectricity refers to the ability of certain materials to generate an electrical charge when subjected to mechanical stress or vibrations. This phenomenon has been widely explored for small-scale applications, such as powering sensors, wearable devices, and low-power electronics. Materials like Lead Zirconate Titanate (PZT) and Zinc Oxide (ZnO) are commonly used in piezoelectric energy harvesting systems due to their high conversion efficiency. While piezoelectric energy harvesting has proven successful in powering small devices, its potential for large-scale energy generation has not been fully explored [11].

In the context of EV charging, piezoelectric harvesters can convert mechanical energy from vehicle movements (e.g., cars driving over roads or parking lots) into electricity. The energy generated from piezoelectric harvesters can provide a continuous power source, independent of weather conditions or time of day. However, the challenges of integrating piezoelectric energy harvesters into large-scale energy systems remain. Wakshume et al. conducted a feasibility study on the use of piezoelectric materials in energy harvesting applications for low-power devices, but large-scale implementation in transportation infrastructure, such as EV charging stations, remains underexplored [12].

The amount of energy produced by piezoelectric materials is typically lower than traditional solar or wind energy systems. For example, piezoelectric systems used in high-traffic areas like parking lots or roads may generate between 50 to 100 W/m² depending on traffic volume and the specific material used. While this output may seem modest, it can contribute significantly to the overall energy supply when integrated with other renewable sources, such as solar energy. The integration of piezoelectric harvesters with solar panels has the potential to create a hybrid charging station that maximizes energy availability by combining the strengths of both energy sources [13].

C. Integrated Solar and Piezoelectric Systems for EV Charging

While solar energy and piezoelectric energy harvesting have been studied independently, few studies have explored their integration into a unified charging station. The combination of solar and piezoelectric systems offers a promising solution to overcome the limitations of each energy source. By integrating solar panels with piezoelectric energy harvesters, charging stations can ensure continuous and reliable energy generation, regardless of weather conditions or time of day. This hybrid approach leverages the complementary characteristics of both energy sources—solar energy providing power during daylight hours, and piezoelectric harvesters generating electricity from mechanical vibrations at all times [14].

Yang et al. explored hybrid energy systems combining solar and piezoelectric energy harvesting for small-scale applications, demonstrating the feasibility of such an integration. However, their study focused on low-power systems and did not address the scalability and efficiency required for large-scale EV charging stations [15]. Similarly, Abedanzadeh et al. proposed a hybrid solar-wind energy system for EV charging, but the integration of piezoelectric energy harvesting into such systems has not been adequately studied [16].

This research seeks to bridge the gap by integrating solar and piezoelectric systems into a unified EV charging station. The proposed system aims to combine the high efficiency of bifacial solar panels with the continuous energy generation potential of piezoelectric energy harvesters, ensuring reliable and sustainable power for EV charging. This integration not only addresses the issue of intermittency associated with solar power but also offers a scalable and environmentally friendly solution for EV infrastructure.

D. Summary

In summary, while solar-powered EV charging stations have proven effective in reducing carbon emissions and supporting the adoption of electric vehicles, their reliance on sunlight limits their energy availability. Piezoelectric energy harvesting, although underutilized in large-scale applications, offers significant potential for continuous power generation from mechanical vibrations. The integration of these two renewable energy sources into a unified charging station has the potential to address the shortcomings of each, providing a reliable and sustainable energy solution for EV infrastructure. This study aims to contribute to the literature by exploring the feasibility, design, and benefits of a dual-source solar and piezoelectric EV charging station, offering a novel approach to achieving reliable, green, and scalable EV charging solutions.

III. PROPOSED SYSTEM

The proposed dual-source charging station integrates two renewable energy sources—solar power and piezoelectric energy harvesting—into a unified system.

This hybrid approach aims to provide a continuous, reliable, and sustainable power supply for Electric Vehicle (EV) charging while addressing the limitations of each energy source. The system architecture is designed to maximize energy capture, ensure efficient power storage and management, and deliver fast and adaptable EV charging solutions.

A. System Architecture

The architecture of the dual-source EV charging station consists of several key components, each playing a specific role in ensuring optimal energy generation, storage, and delivery. The following sections describe each component in detail:

- 1) **Solar Panels (Bifacial with Tracking):** The solar panels are high-efficiency bifacial panels, designed to capture sunlight from both sides of the panel. Bifacial panels have a greater energy conversion efficiency compared to traditional monofacial panels because they can capture reflected sunlight from the ground, significantly improving energy output. These panels are equipped with an advanced tracking system that allows them to adjust their orientation throughout the day, ensuring that they are always positioned to maximize exposure to sunlight. This tracking system ensures that the solar panels collect the most energy possible, particularly during the peak sunlight hours, and helps mitigate the intermittency of solar power during cloudy days by adjusting their angles.
- 2) **Piezoelectric Harvesters:** The piezoelectric harvesters are embedded in high-traffic areas such as roads, parking lots, or driveways, where mechanical stress from vehicles passing over them can generate electricity. These tiles convert the mechanical vibrations into electrical energy, which can then be used to charge the EVs. The piezoelectric materials used in these tiles are selected for their high energy conversion efficiency and durability. By utilizing the kinetic energy of vehicles, the piezoelectric system provides a continuous source of energy that is independent of weather conditions, ensuring that the charging station remains operational even when solar power is unavailable (e.g., at night or on cloudy days).
- 3) **Energy Storage:** The energy storage system is comprised of solid-state batteries and supercapacitors. Solid-state batteries are chosen for their high energy density, long cycle life, and safety advantages over traditional lithium-ion batteries. They store the energy generated by both the solar panels and the piezoelectric harvesters. Supercapacitors are integrated into the system for fast charge and discharge cycles, providing high power density and ensuring that the energy storage system can quickly supply power to the EV charging unit when needed. The combination of solid-state batteries and supercapacitors allows the system to balance the need for high energy capacity (from the batteries) and rapid power delivery (from the supercapacitors), ensuring that EVs can be charged efficiently and quickly.
- 4) **Power Management Unit (PMU):** The Power Management Unit (PMU) plays a crucial role in seamlessly integrating the energy inputs from both the solar panels and the piezoelectric harvesters into the energy storage system. It consists of a multi-input DC-DC converter that ensures the energy generated from both sources is efficiently transferred to the storage system. The PMU also manages the charging and discharging cycles of the batteries and supercapacitors, ensuring that energy is stored when available and discharged when needed. The PMU optimizes the overall performance of the system by monitoring the energy flows, balancing the inputs from solar and piezoelectric sources, and ensuring that the energy storage system is not overcharged or discharged beyond safe limits.
- 5) **Charging Interface:** The Charging Interface is designed to provide fast and efficient charging for EVs. It is compatible with various EV standards, including fast-charging protocols, to ensure that the system can serve a wide range of electric vehicles. The charging interface is designed to deliver high charging power from the stored energy, ensuring that EVs can be charged promptly. The interface is equipped with safety features to protect both the vehicle and the charging station from electrical faults, including overcurrent, overvoltage, and short-circuit protection.

The block diagram below Figure 1 illustrates the key components of the dual-source EV charging station and their interactions:

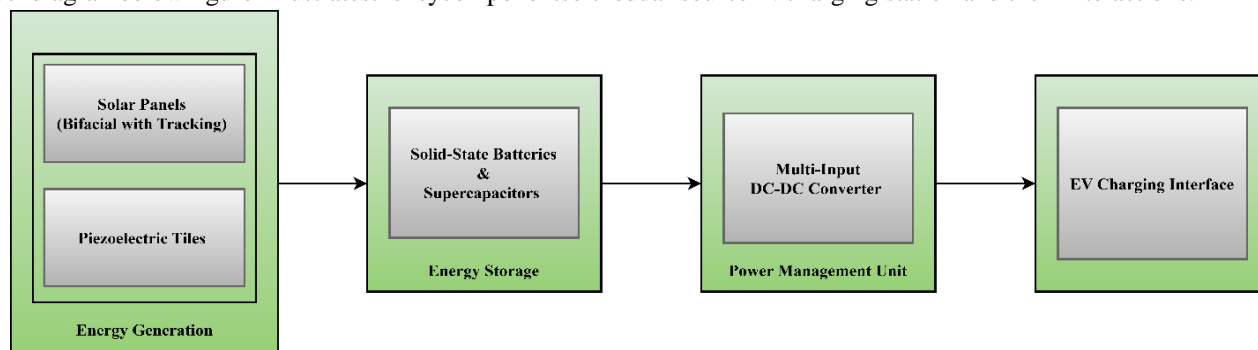


Figure 1: System Block Diagram

B. System Work flow

- 1) **Energy Generation:** Energy is generated from two primary sources: solar panels (via sunlight) and piezoelectric tiles (via mechanical vibrations).
- 2) **Energy Storage:** The generated energy is directed to the energy storage system, where it is stored in solid-state batteries and supercapacitors.
- 3) **Power Management:** The Power Management Unit regulates the flow of energy from the generation sources to the storage and from the storage to the EV charging interface.
- 4) **EV Charging:** The energy stored in the system is used to charge EVs, with the charging interface delivering power to the vehicles by their charging standards.

This integrated approach ensures that the charging station is sustainable and adaptable to varying energy availability, providing a reliable solution for EV users.

C. Key Hardware Components

The proposed dual-source EV charging station integrates advanced hardware components designed to optimize energy generation, storage, and delivery. These components work in concert to ensure efficient and sustainable power management for electric vehicle (EV) charging. Below are the key hardware components of the system, along with their specifications and features (Figure 2 to 7).

1) Solar Panels

a) Specifications:

- Output: 250W per panel
- Type: Bifacial with a dual-axis tracking system
- Efficiency: 85%–90%
- Material: Monocrystalline silicon



Figure 2: Bifacial Solar Panel

b) Features:

- **Bifacial Design:** The bifacial solar panels capture sunlight from both the front and rear sides, significantly enhancing energy generation. By utilizing sunlight reflected from the ground or surrounding surfaces, these panels achieve a higher energy output compared to traditional monofacial panels [17].
- **Dual-Axis Tracking System:** The panels feature a dual-axis tracking system that adjusts their orientation both vertically and horizontally, ensuring they consistently track the sun for maximum energy capture. This system extends operational efficiency, even during periods of low sunlight [18].

2) Piezoelectric Harvesters



Figure3:PiezoElectricHarvestor

- Material: Lead Zirconate Titanate (PZT)
- Energy Output: 50–100 W/m² depending on traffic density
- Placement: Embedded in high-traffic areas such as parking lots, access roads, and driveways, these harvesters capture mechanical energy from vehicles passing over the tiles.
- Durability: Designed to withstand over 1 million mechanical stress cycles, the piezoelectric tiles feature a robust protective layer to resist wear and environmental degradation, ensuring a long lifespan and consistent energy generation [19].

3) Multi-Input DC-DC Converter

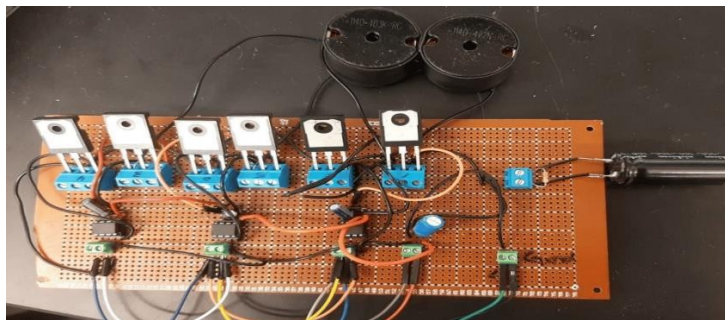


Figure4:Multi Input DC to DC Converter

The Multi-Input DC-DC Converter plays a pivotal role in managing the energy flows from both the solar panels and piezoelectric harvesters, converting variable DC inputs into a stable DC output suitable for EV charging and storage [20].

a) Specifications:

- Efficiency: >95%, ensuring minimal energy loss during conversion.
- Input Voltage Range:
 - Solar Panels: 18V–48V
 - Piezoelectric Tiles: 5V–24V
- Output Voltage Range: Adjustable from 48V to 400V (to meet EV battery charging standards)
- Maximum Input/Output Power: 1kW (scalable for higher capacity systems)
- Conversion Efficiency: Optimized to 95% under typical load conditions.
- Protection Features: Includes overload protection, surge protection, and short-circuit protection to ensure the safety and longevity of the system.

b) Features:

- **Seamless Integration:** Integrates energy from both solar and piezoelectric sources dynamically, adjusting input based on real-time availability.
- **Low Ripple Output:** Ensures stable power delivery to energy storage devices and EVs.
- **Topologies:** Supports Boost and Buck-Boost configurations, offering both step-up and step-down voltage conversion to optimize energy delivery.

4) Energy Storage

The energy storage system utilizes solid-state batteries and supercapacitors to store the generated energy efficiently, handling varying power demands for EV charging [21] & [22].

- **Solid-State Batteries:**



Figure 5: Solid State Batteries

- **Capacity:** 10 kWh per module, providing substantial storage to ensure continuous power supply during low energy generation periods.
- **Advantages:** These batteries offer higher energy density, faster charging, enhanced safety, and longer lifespan compared to traditional lithium-ion batteries.
- **Supercapacitors:**



Figure 6: Super Capacitor Module

- **Role:** Supercapacitors manage transient energy demands, providing rapid bursts of power during peak charging times to facilitate fast EV charging.
- **Lifespan:** Can withstand over 1 million charge/discharge cycles, ensuring durability during frequent power pulses.

5) Monitoring System

The monitoring system tracks real-time performance, ensuring efficient operation by providing insights into both the renewable energy sources and charging station.

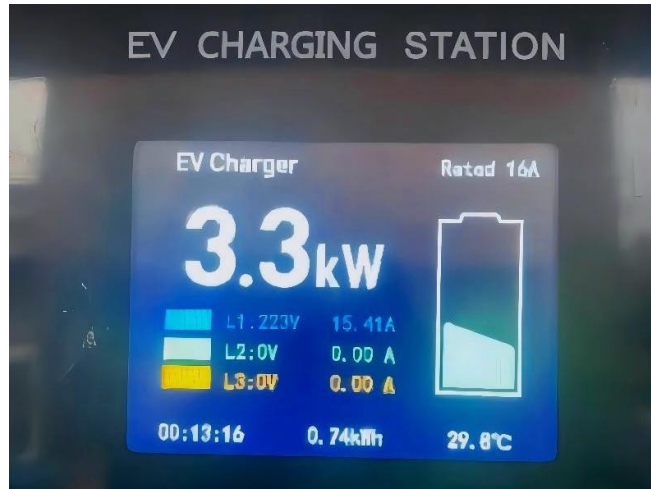


Figure 7: LCD Touchscreen Interface

a) Sensors:

- **Power Monitoring Sensors:** Measure real-time energy output from solar panels and piezoelectric tiles.
- **Environmental Sensors:** Monitor ambient temperature, humidity, and solar irradiance to optimize energy generation.
- **Traffic Sensors:** Detect vehicle movement to assess piezoelectric tile activity.
- **Stress Sensors for Piezoelectric Tiles:** Monitor the mechanical stress exerted by passing vehicles, ensuring optimal performance of the harvesters.

b) Interface:

- **Touchscreen Display:** A 10.1-inch capacitive LCD touchscreen provides an intuitive interface for monitoring system status, including energy generation, storage levels, and EV charging progress. It features multilingual support for global deployment.
- **IoT Integration:** The system is IoT-enabled, allowing remote monitoring and management via Wi-Fi or Ethernet, with real-time data updates every 5 seconds. Mobile and web applications provide remote access, reducing operational costs and downtime.

c) Cloud Integration

- **Platform:** AWS IoT Core or Google Cloud IoT are used for secure data storage and analytics.
- **Features:** Offers remote access to system performance metrics, with predictive analytics for maintenance and efficiency improvement.

d) Advantages

- Provides users with real-time insights into energy utilization and charging progress.
- Enhances reliability through early fault detection and proactive maintenance alerts.
- Supports remote management, reducing operational costs and system downtime.

These key hardware components collectively ensure the dual-source EV charging station is efficient, reliable, and eco-friendly, offering a robust solution for sustainable EV charging.

IV. METHODOLOGY

The methodology section outlines the steps taken to design and integrate the hardware components of the dual-source EV charging station. The process involves carefully planning, installing, and optimizing the system's components to ensure efficient energy generation, storage, and delivery. The following is a detailed explanation of the design and integration process.

A. Design and Integration

1) Solar Panel Setup:

Installation of Bifacial Panels with Dual-Axis Tracking:

The solar panels are installed on the roof or other suitable surfaces. These bifacial panels are chosen for their ability to capture sunlight from both the front and rear sides, thereby improving energy yield compared to standard monofacial panels.

The panels are equipped with a dual-axis tracking system, which allows them to adjust their orientation both horizontally and vertically to follow the sun's movement. This dynamic tracking system maximizes solar energy capture, especially during times of low sunlight, such as early morning or late afternoon.

The tracking system is integrated with the Power Management Unit (PMU) to optimize energy production. The PMU continuously adjusts the flow of energy from the solar panels, ensuring that it is directed efficiently to the energy storage system or directly to the EV charging unit when required.

2) Piezoelectric Tile Installation:

a) Strategic Placement in High-Traffic Zones:

- The piezoelectric tiles are embedded in high-traffic areas such as parking lots, driveways, and access roads. These locations are ideal because they experience constant mechanical stress from moving vehicles, which is converted into electrical energy by the piezoelectric materials embedded in the tiles.
- The tiles are embedded in the ground or road surface, ensuring that vehicles can apply pressure to them as they pass over, generating electricity. This system allows for the harvesting of energy even in areas where solar energy capture is not feasible, such as at night or during overcast weather conditions.

b) Integration with Protective Layers:

- To ensure the durability and longevity of the piezoelectric tiles, they are protected with a weather-resistant and durable layer. This layer shields the piezoelectric elements from physical damage, water infiltration, and environmental wear and tear, extending the lifespan of the system.
- The protective layer also provides insulation, preventing damage to the electrical components of the tiles while allowing for efficient energy harvesting.

3) Energy Storage and Conversion:

a) Integration of Solar and Piezoelectric Outputs:

- The energy generated by both the solar panels and the piezoelectric harvesters is fed into a multi-input DC-DC converter. The converter is designed to handle inputs from both energy sources and convert them into a stable DC output that can be stored in the energy storage system or directly supplied to the EV charging unit.
- The converter ensures that fluctuations in energy generation, such as sudden drops in solar output due to cloud cover, do not negatively impact the performance of the charging station. It manages the energy from the piezoelectric harvesters, which may have varying output based on traffic volume, and ensures that the energy is stored or used optimally.

b) Energy Storage in Batteries and Supercapacitors:

- The converted energy is stored in solid-state batteries and supercapacitors. Solid-state batteries provide high energy density and safety, while supercapacitors handle transient energy demands by quickly discharging energy when required, such as during peak charging times.
- The energy storage system is designed to balance the supply and demand for energy, ensuring that there is always a reserve of energy available for charging EVs, especially during periods of low generation or high demand.

This methodology ensures that the dual-source EV charging station is designed and integrated efficiently, maximizing energy generation and ensuring reliable charging for electric vehicles while utilizing renewable energy sources.

B. Real-Time Monitoring

Real-time monitoring is an essential aspect of the dual-source EV charging station, enabling both users and operators to track system performance and ensure efficient operation.

This section outlines the key features and components of the real-time monitoring system, which includes a user-facing interface and an IoT-based diagnostic infrastructure.

1) *Touchscreen Display for Users:*

a) *Charging Progress Monitoring:*

- A touchscreen display is installed at the charging station to allow users to monitor the status of their electric vehicle (EV) charging. This display provides real-time updates on various metrics such as charging time remaining, energy delivered, and the charge level of the EV's battery.
- The display also provides an indication of the energy flow, showing whether the energy is being sourced from solar panels, piezoelectric harvesters, or the energy storage system. This transparency enhances user experience by keeping them informed on how their vehicle is being charged.

b) *Energy Contributions from Solar and Piezoelectric Sources:*

- The touchscreen also displays a breakdown of the energy contributions from the solar panels and piezoelectric harvesters. This information helps users understand the balance between the two energy sources and highlights the system's efficiency.
- For example, during sunny weather, a larger proportion of the charging energy may come from the solar panels, while on a rainy day or at night, piezoelectric energy could become a more significant contributor. This data also demonstrates the effectiveness of the dual-source design in ensuring consistent energy availability.

2) *IoT-Enabled Sensors for Remote Diagnostics and System Alerts:*

a) *Remote System Monitoring:*

- The charging station is equipped with a network of IoT-enabled sensors that monitor various system parameters in real-time. These sensors track key metrics such as voltage, current, energy output, and the health of the battery and supercapacitor storage systems.
- The sensors are integrated into the overall charging station network, sending data to a central management system. This data is analyzed to identify potential issues and optimize energy management. It also allows operators to keep track of the station's performance remotely, facilitating efficient maintenance and system upgrades.

b) *Real-Time Diagnostics and Alerts:*

- The IoT system is capable of generating alerts in case of system malfunctions or performance degradation. For instance, if the energy output from the solar panels or piezoelectric harvesters drops below a certain threshold, the system will send an alert to the operators.
- Additionally, the system can send maintenance reminders or alert operators if any part of the system, such as the converter or energy storage, is showing signs of wear or malfunction. These alerts ensure that the station remains operational and that any issues are addressed promptly, reducing downtime and increasing the reliability of the charging station.

c) *Data Analytics for Optimization:*

- The collected data from the sensors can also be used for further optimization. By analyzing long-term trends, operators can fine-tune the system for better performance, such as adjusting the solar panel orientation based on seasonal data or optimizing energy storage algorithms to reduce energy loss.

This real-time monitoring system enhances the efficiency, reliability, and user experience of the dual-source EV charging station. It provides both users and operators with actionable insights into the system's performance and ensures that the charging station is always operating optimally.

V. RESULTS AND DISCUSSION

A. Energy Redundancy Over Time

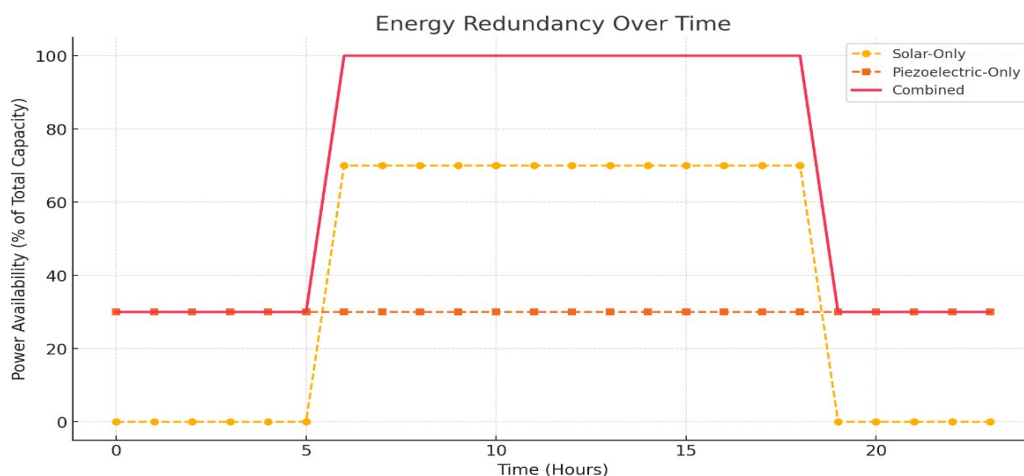


Figure8:Energy RedundancyOverTime

Figure 8 displays the energy output from solar panels, piezoelectric tiles, and their combined output across 24 hours. The solar energy curve peaks during midday, reflecting maximum sunlight exposure between 10 AM and 4 PM. This peak corresponds to the solar panels' optimal operational period, where their bifacial design and tracking system ensure the highest energy capture. However, as expected, the solar output diminishes rapidly during evening hours and drops to zero at night, exposing a critical limitation of standalone solar-powered systems. Conversely, the piezoelectric tiles maintain a consistent energy output throughout the day and night, as their operation depends on mechanical vibrations generated by traffic rather than sunlight. The slight variations in piezoelectric output are attributed to fluctuating traffic patterns, with higher output during peak hours of vehicular activity. The combined energy output showcases the integration of both sources, providing a steady and reliable energy supply. This synergy ensures that even when solar energy is unavailable, piezoelectric energy compensates, guaranteeing 24/7 energy availability. Such redundancy significantly enhances the reliability of the charging station, enabling it to meet the continuous energy demands of EV users without interruptions.

B. Efficiency Comparison

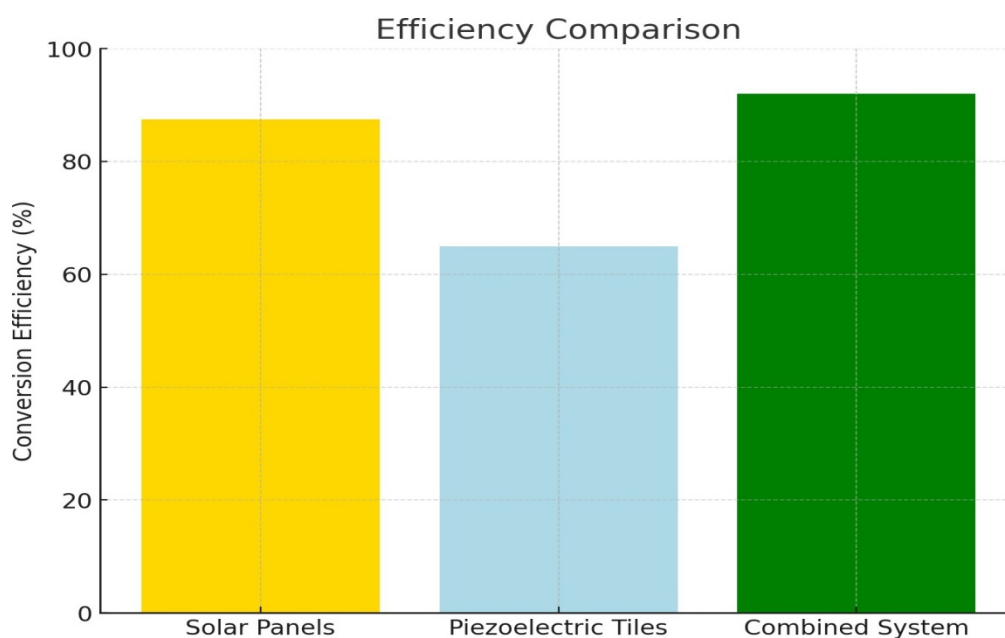


Figure9:EfficiencyComparison

The bar chart (Figure 9) compares the energy conversion efficiencies of individual energy sources—solar panels and piezoelectric tiles—with the efficiency of the integrated system. Solar panels exhibit the highest standalone efficiency, ranging from 85% to 90%, due to their advanced bifacial design and tracking system, which optimize sunlight capture and energy conversion. Piezoelectric tiles, while less efficient at 60% to 70%, are remarkable for their ability to generate energy consistently, irrespective of environmental conditions. The integration of these two energy sources through a multi-input DC-DC converter elevates the overall system efficiency to over 90%. This enhancement is a result of optimized energy management, where the converter minimizes energy losses during conversion and seamlessly combines the output of both sources. The comparison highlights the advantage of integrating complementary renewable energy sources, as the combined system not only maximizes energy utilization but also ensures a more consistent and efficient power supply.

C. Durability of Components

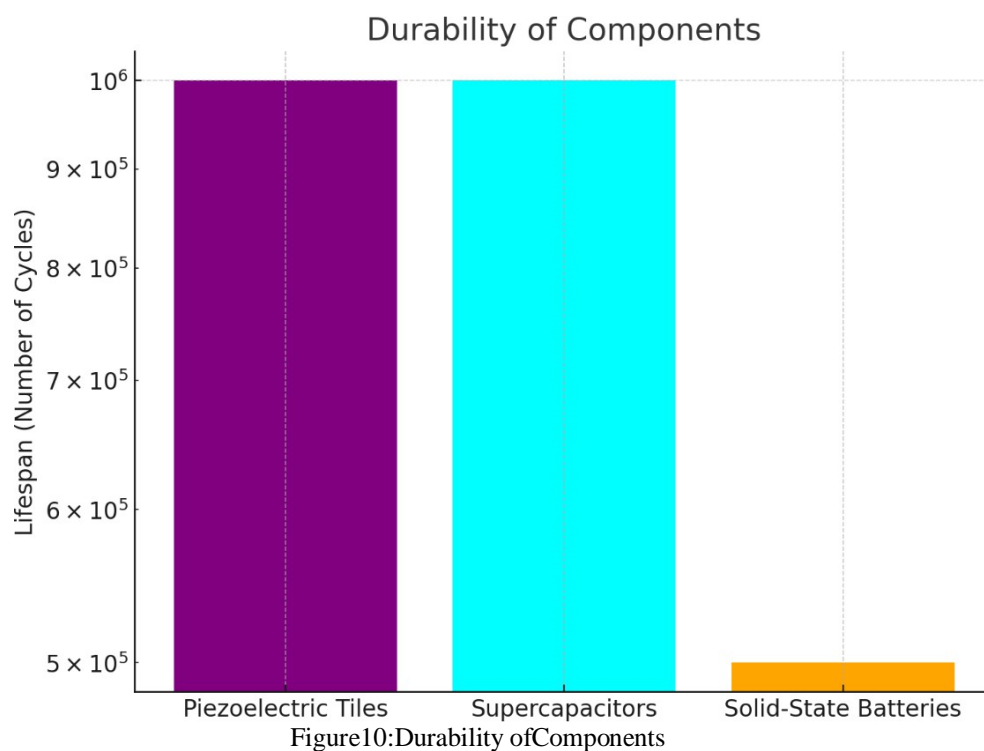


Figure 10: Durability of Components

Figure 10 employs a logarithmic scale to emphasize the longevity of the key hardware components—piezoelectric tiles, supercapacitors, and solid-state batteries. Piezoelectric tiles are designed to endure over 1 million mechanical stress cycles, making them highly suitable for high-traffic zones such as parking lots or access roads. These tiles are equipped with a protective layer that safeguards them from wear and environmental degradation, ensuring long-term performance. Supercapacitors, known for their ability to handle rapid charge and discharge cycles, exhibit a similar lifespan of over 1 million cycles. This makes them ideal for buffering transient energy demands and mitigating sudden spikes in load. Solid-state batteries, while not as long-lasting as supercapacitors, offer significant advantages such as faster charging times, higher energy density, and enhanced safety features compared to traditional lithium-ion batteries. The durability of these components collectively reduces the maintenance frequency and operational downtime of the charging station, ensuring a sustainable and cost-effective solution for EV infrastructure.

D. Energy Contribution Breakdown

The pie chart (Figure 11) provides a breakdown of the energy contributions from solar panels and piezoelectric tiles within the dual-source charging system. Solar panels account for approximately 70% of the total energy output, driven by their high power generation capability during daylight hours.

The bifacial panels, paired with a tracking system, maximize energy capture by utilizing direct sunlight and reflected light from their surroundings. Piezoelectric tiles contribute the remaining 30%, with their output being consistent across day and night. This complementary relationship is pivotal in addressing the limitations of solar power, particularly during cloudy weather or nighttime. By combining these two sources, the system achieves a balanced energy supply, ensuring reliability and sustainability. The energy contribution breakdown underscores the innovative integration of solar and piezoelectric sources, showcasing their ability to work in tandem to meet EV charging demands effectively.

Energy Contribution Breakdown

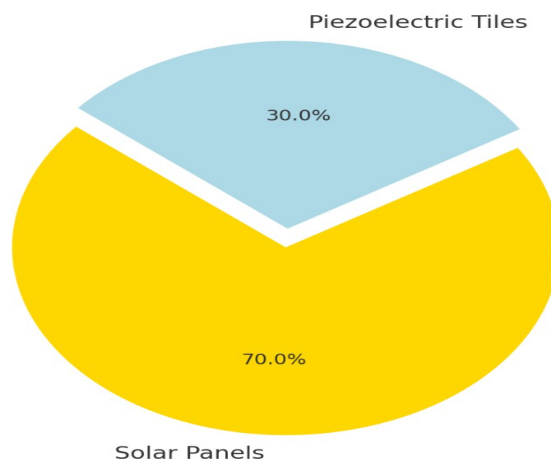


Figure 11: Energy Contribution Breakdown

E. Grid Dependency Reduction Over Time

This line graph (Figure 12) depicts the reduction in grid dependency achieved by implementing the dual-source charging station. Initially, the charging system relies heavily on the grid, especially during nighttime or low-sunlight conditions, leading to higher operational costs and increased carbon emissions. Following the deployment of the dual-source system, grid dependency decreases significantly—by up to 80%—as solar and piezoelectric energy sources fulfill most of the energy requirements. This reduction is most evident during periods of high solar output, where the combined energy from solar panels and piezoelectric tiles exceeds the station's demand. Even during nighttime or cloudy weather, piezoelectric energy continues to provide a substantial portion of the required power, further reducing the reliance on grid electricity. This achievement not only minimizes operational expenses but also contributes to environmental sustainability by lowering fossil fuel consumption. The graph effectively demonstrates the long-term impact of the proposed system in fostering energy independence and supporting the transition to a greener EV charging infrastructure.

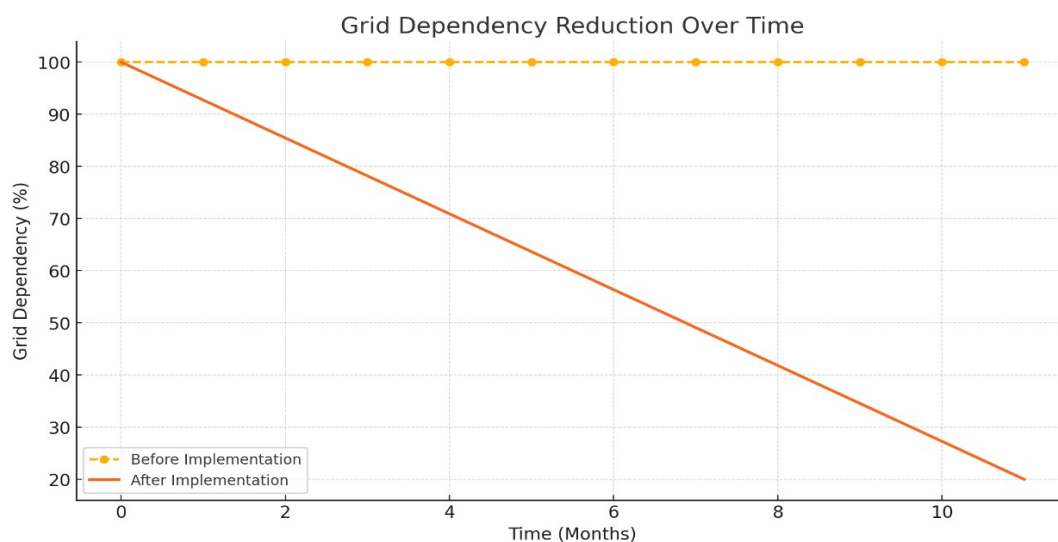


Figure 12: Grid Dependency Reduction Over Time

VI. DISCUSSION

The results highlight the innovative integration of solar and piezoelectric energy sources in the dual-source EV charging system. The energy redundancy graph underscores the complementary nature of these sources, with solar panels delivering peak energy during midday and piezoelectric tiles providing consistent output throughout the day and night. This integration ensures uninterrupted energy availability, addressing the limitations of standalone systems reliant on sunlight. The efficiency comparison demonstrates the superior performance of the integrated system, achieving over 90% efficiency through optimized energy management with a multi-input DC-DC converter, compared to the standalone efficiencies of solar panels (85%-90%) and piezoelectric tiles (60%-70%).

The durability analysis highlights the longevity of key components, including piezoelectric tiles capable of withstanding over 1 million mechanical cycles and supercapacitors designed for rapid charge and discharge cycles. Solid-state batteries, while offering slightly lower durability, provide significant advantages such as faster charging and higher energy density, ensuring reliability and minimal maintenance. The energy contribution breakdown reveals that solar panels contribute 70% of the energy, leveraging their advanced bifacial design, while piezoelectric tiles account for 30%, offering consistent output irrespective of environmental conditions. This balance addresses solar energy's limitations and enhances overall system reliability.

Finally, the grid dependency reduction graph showcases a substantial decrease in reliance on grid electricity—up to 80%—due to the combined energy contributions of solar and piezoelectric sources. This reduction not only lowers operational costs but also promotes environmental sustainability by minimizing fossil fuel consumption. The results collectively demonstrate the system's effectiveness in delivering a reliable, efficient, and sustainable energy solution for EV charging.

VII. CONCLUSION

The dual-source solar and piezoelectric EV charging station offers an innovative and sustainable solution to address the growing energy demands of electric vehicles (EVs). By integrating high-efficiency bifacial solar panels and durable piezoelectric tiles, the system ensures reliable energy availability around the clock. Advanced hardware components, such as a multi-input DC-DC converter, solid-state batteries, and supercapacitors, contribute to seamless energy management, optimized storage, and faster power delivery. The incorporation of real-time monitoring further enhances user convenience by providing live updates on energy contributions and charging progress, while IoT-enabled sensors enable remote diagnostics and system alerts.

The following graphs were instrumental in highlighting the system's performance and advantages:

- 1) **Energy Redundancy Over Time:** Demonstrates the complementary relationship between solar and piezoelectric sources, ensuring 24/7 energy availability.
- 2) **Efficiency Comparison:** Illustrates the enhanced conversion efficiency achieved by integrating the two energy sources through a multi-input DC-DC converter.
- 3) **Durability of Components:** Emphasizes the long lifespan of piezoelectric tiles, supercapacitors, and solid-state batteries, reducing maintenance and enhancing system reliability.
- 4) **Energy Contribution Breakdown:** Highlights the balanced energy supply achieved by combining solar (70%) and piezoelectric (30%) sources.
- 5) **Grid Dependency Reduction Over Time:** Showcases the significant reduction in grid dependency (up to 80%) achieved by leveraging renewable energy sources.

This dual-source EV charging station represents a significant advancement in sustainable transportation infrastructure, addressing the challenges of energy redundancy, efficiency, and environmental impact. It exemplifies how the integration of renewable energy technologies can contribute to a greener and more reliable future for electric mobility.

VIII. FUTURE WORK

Future research will aim to further enhance the dual-source EV charging station's performance, scalability, and adaptability. A key focus will be on scaling the system for commercial and large-scale deployment, which involves addressing challenges such as cost reduction, infrastructure compatibility, and widespread integration with existing EV networks. Additionally, advancements in piezoelectric materials will be explored to improve their energy conversion efficiency and durability, ensuring sustained performance under high-traffic conditions. The integration of artificial intelligence (AI) will be prioritized to enable predictive energy management.

AI algorithms can optimize the allocation of energy from solar and piezoelectric sources by analyzing usage patterns, weather forecasts, and traffic data.

This predictive approach can enhance energy efficiency, reduce dependency on grid power, and ensure uninterrupted operation. Furthermore, incorporating machine learning techniques will enable dynamic system adaptation to varying energy demands, ensuring a smarter and more resilient charging infrastructure.

Future efforts will also focus on extending the IoT-enabled monitoring system to include advanced analytics and real-time fault detection, which will enhance the overall reliability and user experience. These advancements will help transform the proposed system into a commercially viable solution, making a substantial contribution to sustainable transportation infrastructure.

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