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

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Abstract: ElectricVehicles(EVs)arepivotalinreducinggreenhousegasemissionsanddiminishingreliance 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 energyharvestingtodelivercontinuous,sustainableenergyforEVcharging. The system features bifacial solar panelswithdual-axistracking,maximizingenergycaptureby harnessingdirectand 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 promotesreducedcarbonemissions, robustreliability, andenhanceduserconvenience,offeringa transformative solution for sustainable EV charging infrastructure.
Keywords: ElectricVehicles(EVs),Dual-SourceChargingStation,RenewableEnergyIntegration,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 sustainablechargininfrastructure.Theavailabilityofsuchinfrastructureiscrucialforsupporting the growing EV fleet and ensuring a seamless user experience [2].

TraditionalEVcharging stationstypicallyrelyongrid orsolarenergytochargeelectricvehicles. 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 influencedbyweatherconditionsandtimeofday.Forinstance,solarpanelsproducelittletonoenergy 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-scaleenergygeneration,especiallyinthecontextofEVcharging,remainslargelyuntapped.

Theabilitytocaptureenergyfrommechanicalvibrationsormovements—suchasthosegenerated byvehiclesdrivingover roadsor parking inhigh-trafficareas—offersaconsistentandrenewable power source. When implemented in high-traffic zones, piezoelectric energy harvesters can continuouslygeneratepower,evenduringovercastweatherornighttimehours,ensuringareliable energy source for EV charging stations [6].This research proposes a novel dual-source EV charging station that integrates both solar and piezoelectricenergyharvestingtechnologies.Bycombiningthesetworenewableenergysources, the system capitalizes on the complementary strengths of each. Solar power provides energy during the day, while piezoelectric harvesters generate electricity from vehicle movements, ensuringcontinuouspoweravailabilityregardlessofweatherconditionsortimeofday.

Thisdual- 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 sunlightfromboththe frontandrearsurfacesofthepanel,increasingenergygenerationefficiency. Alongsidethis,piezoelectricenergyharvestersembeddedinhigh-trafficareas,suchasparkinglots 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 assolid-statebatteriesand supercapacitors, whichprovide efficientenergystorageandfastpower 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, thesystemnot only addresses the challengesofenergy intermittency andavailabilitybut alsoprovidesascalablesolutionwiththepotentialforwidespreaddeployment.Thisresearchaims todemonstrate the feasibility and advantages ofcombiningsolarandpiezoelectric 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, piezoelectricenergy harvesting,and theirintegrationpotential. Section3,ProposedSystem,elaborates on the architecture, including bifacial solar panels, piezoelectric harvesters, energy storage solutions, and power management components. Section 4, Methodology, outlines the design,installation,andoptimizationprocessforthesystem'scomponents.Section5,Resultsand Discussion, presents the key findings, including energy efficiency, component durability, energy contributions,and griddependencyreduction ,supportedbyvisualdatarepresentations.Section6, 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

ThedevelopmentofElectricVehicle(EV)charginginfrastructurehasbecomeapriorityglobally, 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, variousenergysourceshavebeenexploredtopowerthesestations,withsolarenergybeingoneof the most popular renewable sources. However, while solar-powered EV charging stations offer a clean and renewablesolution, theyfaceinherent limitations primarily related to theintermittency of sunlight [7]. Additionally, piezoelectric energy harvesting, which has primarily been explored forsmall-scaleapplications,hassignificantpotentialforlarge-scaleenergygenerationbuthasnot yetbeenfully integrated intomainstreamEVcharginginfrastructure[8].Thissectionreviewsthe existingliteratureonsolar-poweredchargingstations, andpiezo electricenergysystems ,andhow integratingthesetechnologiescouldofferamorereliableandsustainablesolutionforEVcharging.

A. Solar-Powered EV Charging Stations

Solarenergyisoneofthemostwidelyusedrenewablesourcesforpoweringchargingstations. 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 demonstratedthatsuchstationscouldcontributetogreenenergygoalsbyreducingdependencyon the grid and lowering CO2 emissions [9].

However,themajorlimitationofsolarpowerisitsdependenceonweatherconditionsandtimeofday.Whilesolarenergyisabundantinsunnyregions,itsavailabilitysignificantlydecreasesduringcloudyweatheroratnight,leadingtogapsinenergyavailabilityforEVcharging.Toaddresst hese 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,thisapproachstilldependsontheavailabilityofsunlight,makingitlesseffectiveduring 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 subjectedtomechanicalstressorvibrations.Thisphenomenonhasbeenwidelyexploredforsmall- scale applications, such as powering sensors, wearable devices, and low-power electronics. Materials like Lead ZirconateTitanate (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 ontheuseofpiezoelectricmaterialsinenergyharvestingapplicationsforlow-powerdevices,but large-scaleimplementationintransportationinfrastructure ,suchasEVchargingstations,remains underexplored [12].

Theamountofenergyproducedbypiezoelectricmaterialsistypicallylowerthantraditionalsolarorwindenergysystems.Forexample,piezoelectricsystemsusedinhigh-trafficareaslikeparkinglotsorroadsmaygeneratebetween50to100W/m²dependingontrafficvolume andthespecific material used. While this output may seem modest, it can contribute significantly to the overall energysupplywhenintegratedwithotherrenewablesources,suchassolarenergy.Theintegration 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 ensurecontinuousandreliableenergygeneration,regardlessofweatherconditionsortimeofday. This hybrid approach leverages the complementary characteristics of both energysources—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 bridgethegap by integrating solarand piezoelectric systems into aunified EV charging station. The proposed system aims to combine the high efficiency of bifacial solar panelswiththecontinuousenergygenerationpotential ofpiezoelectricenergyharvesters,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 thepotential to address theshortcomings of each, providing areliable 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

Theproposeddual-sourcechargingstationintegratestworenewableenergysources—solarpower andpiezoelectricenergyharvesting—intoaunifiedsystem.

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Thishybridapproachaimstoprovide a continuous, reliable, and sustainable power supply for Electric Vehicle (EV) charging while addressingthelimitationsofeachenergysource.Thesystemarchitectureisdesignedtomaximize energy capture, ensure efficient power storage and management, and deliver fast and adaptable EV charging solutions.

A. System Architecture

ThearchitectureofthedualsourceEVchargingstationconsistsofseveralkeycomponents,eachplayingaspecificroleinensuringoptimalenergygeneration,storage,anddelivery.Thefollowing 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 theycancapturereflectedsunlightfromtheground,significantlyimprovingenergyoutput. These panels are equipped with an advanced tracking system that allows them to adjust theirorientationthroughouttheday, ensuringthattheyarealways positionedtomaximize 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) PiezoelectricHarvesters:Thepiezoelectricharvestersareembeddedinhigh-trafficareas such as roads, parking lots, or driveways, where mechanical stress from vehicles passingover 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. Byutilizingthekineticenergyofvehicles, thepiezoelectricsystem providesacontinuous 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 piezoelectricharvestersintotheenergystoragesystem.Itconsistsofamulti-inputDC-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 batteriesandsupercapacitors,ensuringthat energyisstoredwhenavailableanddischarged 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, ensuringthatEVscanbechargedpromptly.Theinterfaceisequippedwithsafetyfeatures to protect both the vehicle and the charging station from electrical faults, including overcurrent, overvoltage, and short-circuit protection.

TheblockdiagrambelowFigure1illustratesthekeycomponentsofthedual-sourceEVcharging station and their interactions:

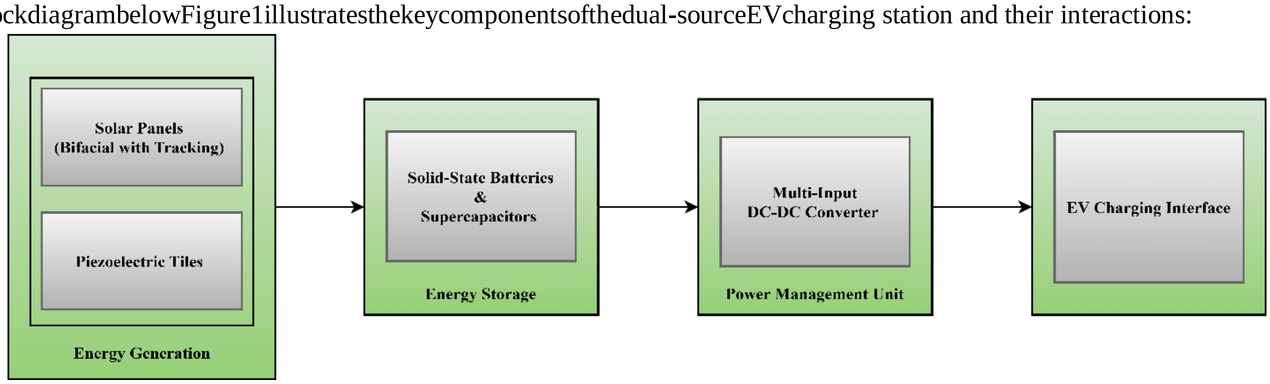

Figure1:System Block Diagram

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B. System Work flow

1) EnergyGeneration:Energyisgeneratedfromtwoprimarysources:solarpanels(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) PowerManagement:ThePowerManagementUnitregulatestheflowofenergyfromthe 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 sustainableand adaptableto varying energy availability, providing a reliable solution for EV users.

C. KeyHardware Components

The proposed dual-source EV charging station integrates advanced hardware components designed tooptimizeenergy generation,storage,anddelivery.Thesecomponentsworkinconcert to ensure efficient and sustainable power management for electric vehicle (EV) charging. Below arethekeyhardwarecomponentsofthesystem,alongwiththeirspecificationsandfeaturesFigure 2 to 7.

1) Solar Panels

a) Specifications:

- Output:250Wper panel
- Type:Bifacialwithadual-axistrackingsystem
- Efficiency:85%–90%
- Material:Monocrystalline silicon

Figure2:Bifacial SolarPanel

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

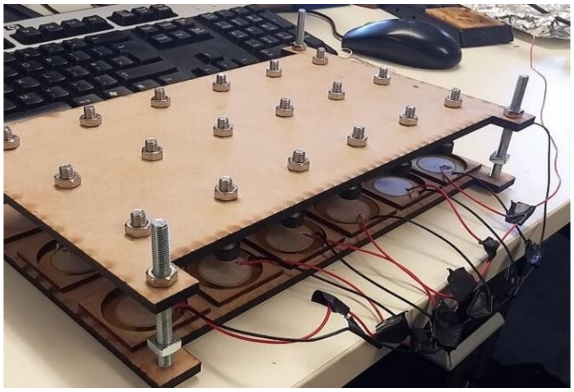

Figure3:PiezoElectricHarvestor

- Material:LeadZirconateTitanate(PZT)
- EnergyOutput:50–100 W/m²depending ontraffic density
- Placement: Embedded in high-traffic areas such as parking lots, access roads, and driveways,theseharvesterscapturemechanicalenergyfromvehiclespassingoverthetiles.
- 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-InputDC-DCConverter

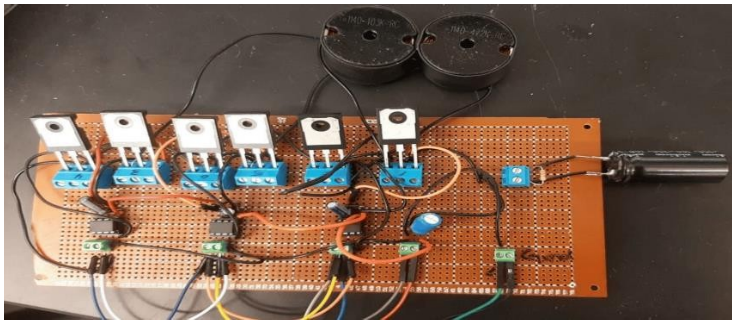

Figure4:Multi InputDCtoDCConverter

The Multi-Input DC-DC Converter plays a pivotal role in managing the energy flows from both thesolarpanelsandpiezoelectricharvesters,convertingvariableDCinputsintoastableDCoutput suitable for EV charging and storage [20].

a) Specifications:

- Efficiency:>95%,ensuringminimalenergylossduring conversion.
- InputVoltage Range:
  - SolarPanels: 18V–48V
  - PiezoelectricTiles:5V–24V
- OutputVoltageRange:Adjustablefrom48Vto400V(tomeetEVbatterycharging standards)
- MaximumInput/OutputPower:1kW(scalableforhighercapacitysystems)
- ConversionEfficiency:Optimizedto95%under typicalloadconditions.
- ProtectionFeatures:Includesoverloadprotection,surgeprotection,andshort-circuit protection to ensure the safety and longevity of the system.

b) Features:

- SeamlessIntegration:Integratesenergyfrombothsolarandpiezoelectricsourcesdynamically, adjusting input based on real-time availability.
- LowRippleOutput:EnsuresstablepowerdeliverytoenergystoragedevicesandEVs.
- Topologies:SupportsBoostandBuck-Boostconfigurations,offeringbothstep-upand step-down voltage conversion to optimize energy delivery.

4) Energy Storage

Theenergystoragesystem utilizes solid-statebatteries and supercapacitors to storethe generated energy efficiently, handling varying power demands for EV charging [21] & [22].

- Solid-StateBatteries:

Figure5:SolidStateBatteries

- Capacity: 10 kWh per module, providing substantial storage to ensure continuous power supply during low energy generation periods.
- Advantages:Thesebatteriesofferhigherenergydensity,fastercharging,enhancedsafety, and longer lifespan compared to traditional lithium-ion batteries.
- Supercapacitors:

Figure6:SuperCapacitor Module

- Role:Supercapacitorsmanagetransientenergydemands,providingrapidburstsofpower during peak charging times to facilitate fast EV charging.
- Lifespan:Canwithstandover1millioncharge/dischargecycles,ensuringdurability during frequent power pulses.

5) Monitoring System

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

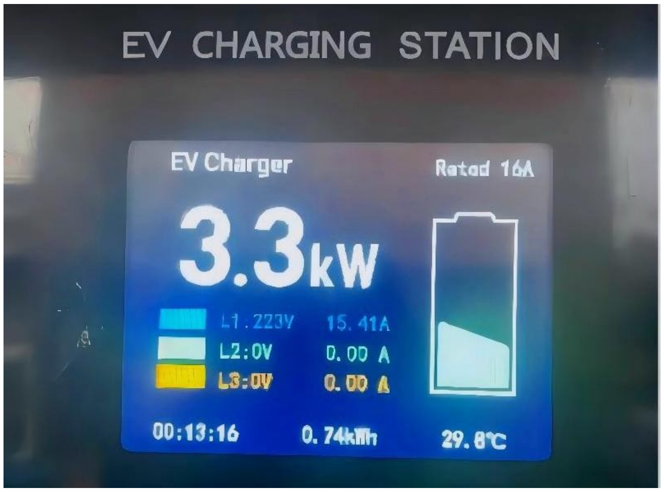

Figure7:LCDTouchscreenInterface

a) Sensors:

- PowerMonitoringSensors:Measurereal-timeenergyoutputfromsolarpanelsand piezoelectric tiles.
- EnvironmentalSensors: Monitorambienttemperature,humidity,andsolarirradianceto optimize energy generation.
- TrafficSensors:Detectvehiclemovementtoassesspiezoelectrictileactivity.
- StressSensorsforPiezoelectricTiles: Monitor themechanicalstressexertedbypassing vehicles, ensuring optimal performance of the harvesters.

b) Interface:

- Touchscreen Display: A 10.1-inch capacitive LCD touchscreen provides an intuitive interfaceformonitoringsystemstatus,includingenergygeneration,storagelevels,andEV 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

- Providesuserswithreal-timeinsightsintoenergyutilizationandcharging progress.
- Enhancesreliabilitythroughearlyfaultdetectionandproactivemaintenance alerts.
- Supportsremotemanagement,reducing operationalcostsandsystem 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

Themethodologysectionoutlinesthestepstakentodesignandintegratethehardwarecomponents 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:

InstallationofBifacialPanelswith 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.ThePMUcontinuouslyadjuststheflowofenergyfromthesolarpanels,ensuringthat it is directed efficiently to the energy storage system or directly to the EV charging unit when required.

2) PiezoelectricTileInstallation:

a) StrategicPlacementinHigh-TrafficZones:

- Thepiezoelectrictiles are embedded in high-traffic areas such as parking lots, driveways, and access roads. These locations are ideal because they experience constant mechanicalstressfrommovingvehicles,whichisconvertedintoelectricalenergybythepiezoelectric 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) IntegrationwithProtective 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) IntegrationofSolarandPiezoelectricOutputs:

- Theenergygeneratedbyboth® thesolarpanelsandthepiezoelectricharvestersisfedintoa multi-inputDC DCconverter. The converterisdesignedtohandleinputsfrombothenergy 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.
- Theconverterensuresthatfluctuationsinenergygeneration,suchassuddendropsinsolar 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) EnergyStoragein Batteriesand 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-TimeMonitoring

Real-timemonitoringisanessentialaspectofthe dual-sourceEVchargingstation,enablingboth 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) *TouchscreenDisplayfor Users:*
a) *ChargingProgressMonitoring:*
- Atouchscreendisplayisinstalledatthechargingstationtoallowuserstomonitorthestatusoftheirelectricvehicle(EV)charging.Thisdisplayprovidesreal-timeupdatesonvariousmetricssuchaschargingtimeremaining,energydelivered,andthechargeleveloftheEV'sbattery.
- Thedisplayalsoprovidesanindicationoftheenergyflow,showingwhethertheenergyis 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) *EnergyContributionsfromSolarandPiezoelectricSources:*
- 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.
- Forexample, duringsunny weather,alargerproportion ofthechargingenergymay come fromthesolarpanels, whileonrainyday soratnight, piezoelectricenergycouldbecomea more significant contributor. This data also demonstrates the effectiveness of the dual- source design in ensuring consistent energy availability.

2) *IoT-EnabledSensorsforRemoteDiagnosticsandSystem Alerts:*
a) *RemoteSystem 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 centralmanagementsystem.Thisdataisanalyzedtoidentifypotentialissuesandoptimize energy management. It also allows operators to keep track of the station's performance remotely, facilitating efficient maintenance and system upgrades.

b) *Real-TimeDiagnosticsandAlerts:*
- The IoT system is capable of generating alerts in case of system malfunctions or performancedegradation.Forinstance,iftheenergyoutputfromthesolarpanelsorpiezoelectric 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) *DataAnalyticsforOptimization:*
- Thecollecteddatafromthesensorscanalsobeusedforfurtheroptimization.Byanalyzing 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-sourceEVchargingstation.Itprovidesbothusersandoperatorswithactionableinsightsinto the system's performance and ensures that the charging station is always operating optimally.

V. RESULTS AND DISCUSSION

A. *Energy Redundancy Over Time*

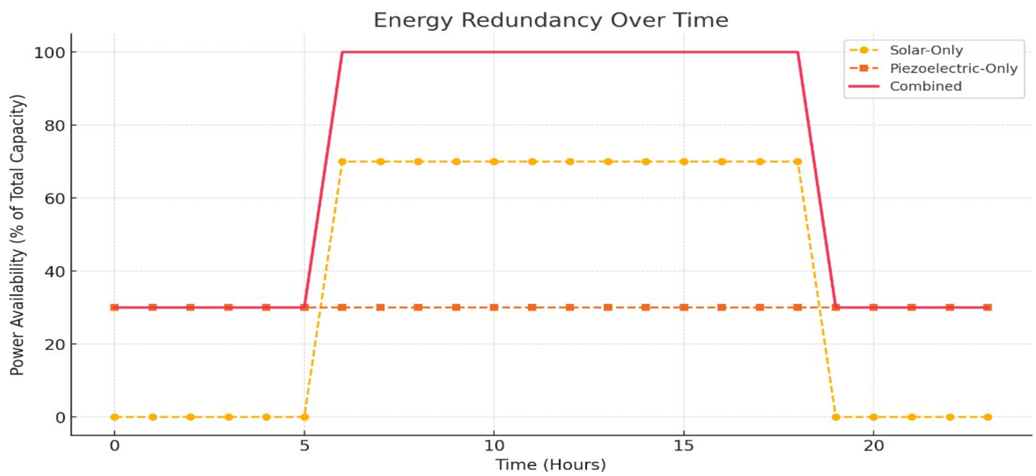

Figure8:Energy RedundancyOverTime

Figure 8 displays the energy output from solar panels, piezoelectric tiles, and their combined outputacross24hours.Thesolarenergycurvepeaksduringmidday,reflectingmaximumsunlight exposurebetween10AMand4PM.Thispeakcorrespondstothesolarpanels'optimaloperational period, where their bifacial design and tracking system ensure the highest energy capture. However,as expected,thesolaroutputdiminishes rapidlyduring eveninghoursanddropstozero 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 duringpeakhoursofvehicularactivity.Thecombinedenergyoutputshowcasestheintegrationof bothsources,providingasteadyandreliableenergysupply.Thissynergyensuresthatevenwhen 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

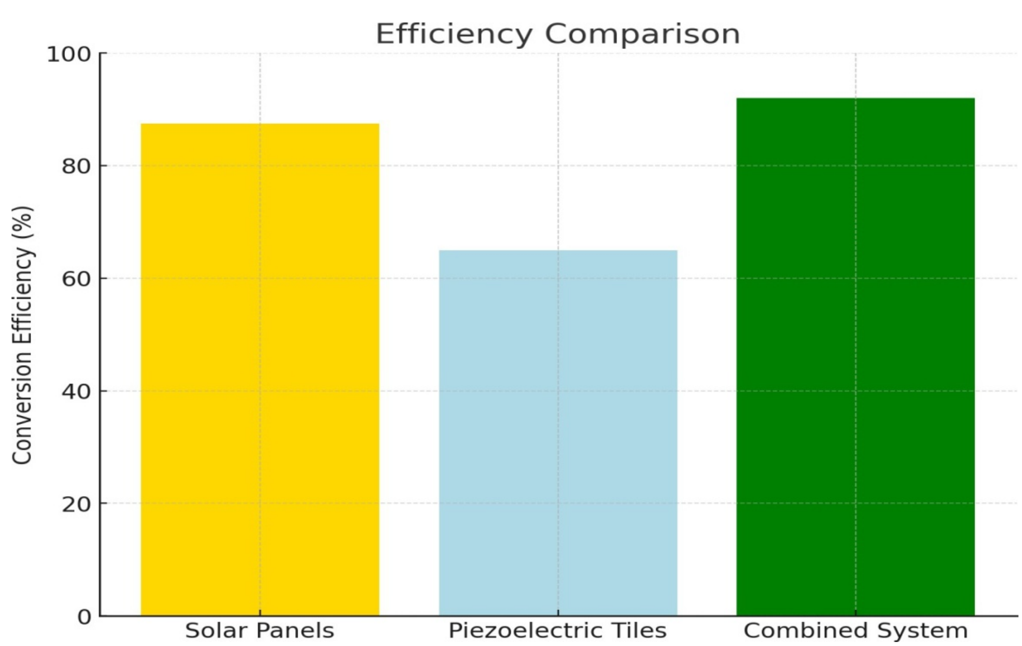

Figure9:EfficiencyComparison

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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 panelsexhibitthehigheststandalone efficiency,rangingfrom85%to90%,duetotheiradvanced bifacial design and tracking system, which optimize sunlight capture and energy conversion. Piezoelectric tiles, while less efficient at 60% to 70%, areremarkable for their ability to generate energyconsistently,irrespectiveofenvironmentalconditions.Theintegrationofthesetwoenergy 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 minimizesenergylossesduringconversionandseamlesslycombinestheoutputsofbothsources. Thecomparisonhigh lightstheadvantageof integratingcomplementaryrenewableenergysources, asthecombined system notonlymaximizesenergy utilizationbutalsoensuresamoreconsistent and efficient power supply.

C. Durability of Components

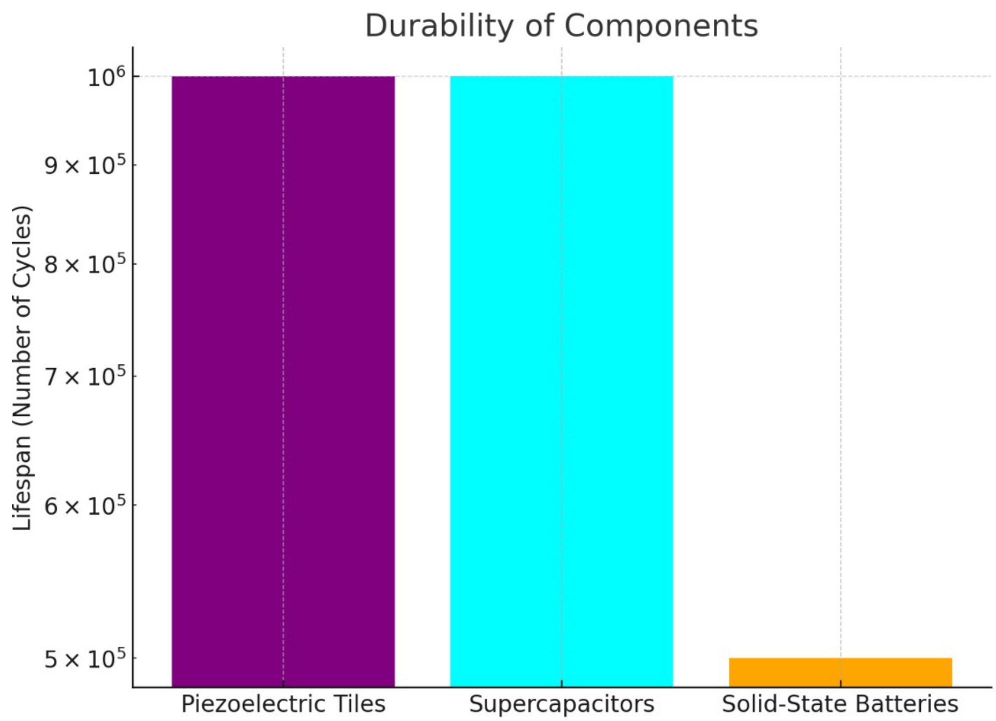

Figure10:Durability ofComponents

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 designedtoendureover 1millionmechanicalstresscycles,makingthemhighlysuitableforhigh- traffic zones such as parking lots oraccess roads. Thesetilesare equipped with aprotectivelayer thatsafeguardsthemfromwearandenvironmentaldegradation,ensuringlong-termperformance. 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,offersignificantadvantagessuchasfasterchargingtimes,higherenergydensity, andenhancedsafetyfeaturescomparedtotraditionallithium-ionbatteries.Thedurabilityofthese 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

Thepiechart(Figure11)providesabreakdownoftheenergycontributionsfromsolarpanelsand piezoelectrictileswithinthedual-source charging system. Solarpanelsaccountforapproximately 70% of the total energy output, driven by their high power generation capability during daylight hours.

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Thebifacialpanels,pairedwithatrackingsystem,maximizeenergycapturebyutilizing 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,ensuringreliab ilityandsustainability.Theenergycontributionbreakdownunderscoresthe innovative integration of solar and piezoelectric sources, showcasing their ability to work in tandem to meet EV charging demands effectively.

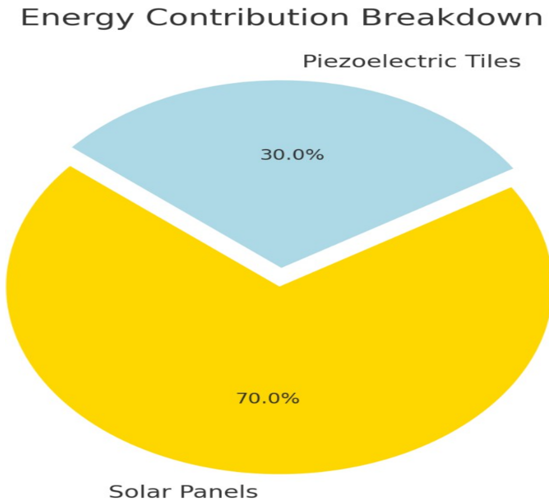

Figure11:EnergyContributionBreakdown

E. Grid Dependency Reduction OverTime

This line graph (Figure 12) depicts the reduction in grid dependency achieved by implementing thedual-sourcechargingstation.Initially,thechargingsystemreliesheavilyonthegrid,especially during nighttime or low-sunlight conditions, leading to higher operational costs and increased carbonemissions.Following thedeployment ofthedual-sourcesystem, grid dependencydecreases significantly—byupto80%—assolarandpiezoelectricenergysourcesfulfillmostofthe 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 duringnighttimeorcloudyweather,piezoelectricenergycontinuestoprovideasubstantialportion oftherequiredpower,furtherreducingtherelianceongridelectricity.Thisachievementnotonly minimizes operational expenses but also contributes to environmental sustainability by lowering fossilfuelconsumption.Thegrapheffectivelydemonstratesthelong-termimpactoftheproposed system in fostering energy independence and supporting the transition to a greener EV charging infrastructure.

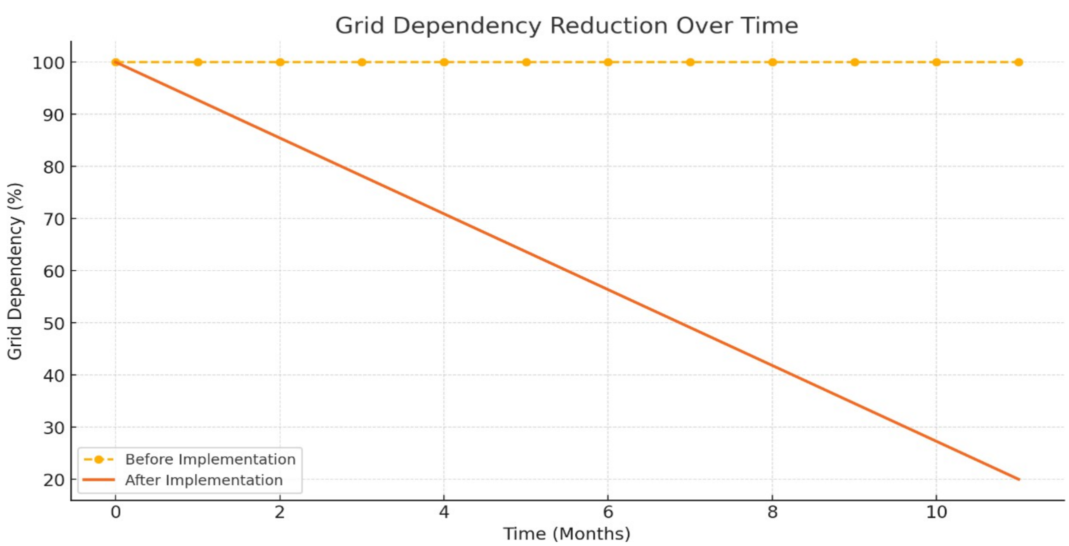

Figure12:GridDependencyReductionOverTime

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VI. DISCUSSION

The results highlight the innovative integration of solar and piezoelectric energy sources in the dual-sourceEVchargingsystem.Theenergyredundancygraphunderscoresthecomplementarynatureofthesesources,withsolarpanelsdelivering peakenergyduringmiddayandpiezoelectric 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,achievingover 90%efficiency throughoptimize denergymanagementwithamulti-input DC-DC converter, compared to the standalone efficiencies of solar panels (85%-90%) and piezoelectric tiles (60%-70%).

Thedurabilityanalysishighlightsthelongevityofkeycomponents,includingpiezoelectrictiles capable of withstanding over 1 million mechanical cycles and supercapacitors designed for rapid chargeanddischargecycles.Solid-statebatteries, whileofferingslightly lowerdurability,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%oftheenergy, leveragingtheiradvancedbifacialdesign,whilepiezoelectrictilesaccountfor 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 gridelectricity—upto80%—duetothecombinedenergycontributionsofsolarandpiezoelectric sources. This reduction not only lowers operational costs but also promotes environmental sustainabilitybyminimizingfossilfuelconsumption.Theresultscollectivelydemonstratethe 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.

Thefollowinggraphswereinstrumentalinhighlightingthesystem'sperformanceandadvantages:

1) EnergyRedundancyOverTime:Demonstratesthecomplementaryrelationshipbetween 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. Akey focus will beon scaling thesystem for commercial and large- scale deployment, which involves addressing challenges such as cost reduction, infrastructure compatibility,andwidespreadintegrationwithexistingEVnetworks.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 canenhanceenergyefficiency, reducedependencyongrid power,andensure uninterrupted operation. Furthermore, incorporating machine learning techniques will enable dynamic system adaptation to varying energy demands, ensuring a smarter and more resilient charging infrastructure.

FutureeffortswillalsofocusonextendingtheIoT-enabledmonitoringsystemtoincludeadvanced 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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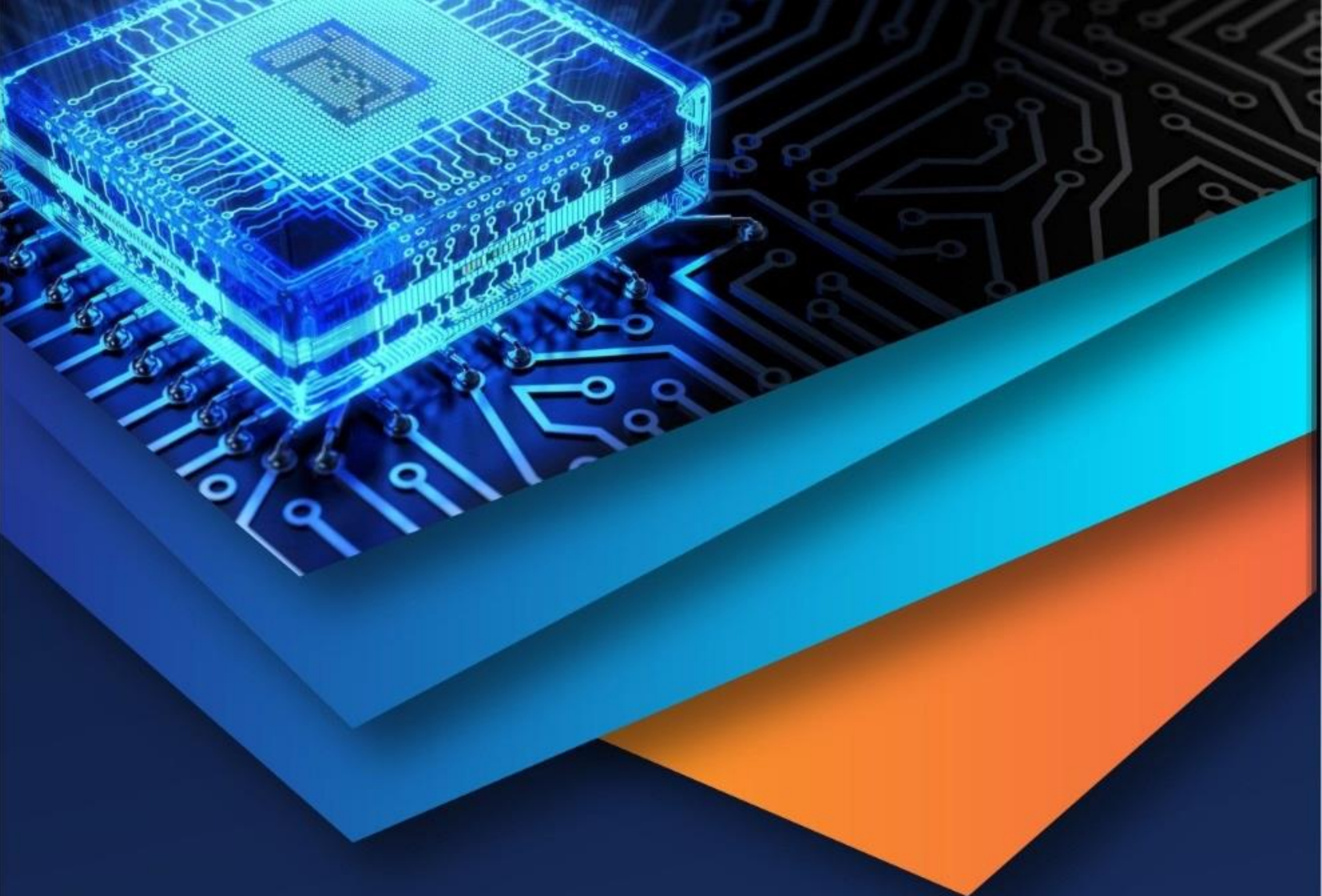

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