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A REVIEW OF SOLAR-POWERED ELECTRIC VEHICLE CHARGING STATIONS: TECHNOLOGIES, CHALLENGES, AND FUTURE TREND

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Abstract

Rapid urbanization, industrialization, and population growth have increased global energy demand, creating serious environmental and economic challenges. The transport sector remains a major source of CO_2 emissions because of its heavy dependence on petroleum-based fuels. In response, the rapid growth of electric vehicles (EVs) has increased the need for sustainable and environmentally friendly charging infrastructure. Solar-powered EV charging stations offer a promising solution by using renewable energy to reduce emissions and support clean transportation. These systems combine photovoltaic (PV) panels, battery energy storage systems, and smart charging technologies to provide clean and reliable electricity for EV charging. This review paper examines the key technologies, challenges, and future trends related to solar-powered EV charging stations. It discusses grid-connected, off-grid, and hybrid charging systems, along with the integration of artificial intelligence (AI), the Internet of Things (IoT), and energy management systems. The paper also highlights major challenges, including high installation costs, weather dependency, battery storage limitations, and charging speed issues. Possible solutions such as smart charging strategies, advanced batteries, and hybrid renewable systems are also analyzed. The findings suggest that solar-powered EV charging stations can play an important role in supporting sustainable transportation, reducing CO_2 emissions, and promoting renewable energy development in the future.

1. Introduction

Nowadays, the increasing demand for clean energy and sustainable transportation has accelerated the development of electric vehicles (EVs) and renewable energy technologies. Growing environmental concerns, rapid depletion of fossil fuels, and rising greenhouse gas emissions have encouraged governments, industries, and researchers to explore eco-friendly alternatives to conventional transportation systems. As a result, solar-powered electric vehicle charging stations have emerged as a promising solution for reducing carbon emissions and supporting sustainable energy development. These charging systems integrate photovoltaic (PV) technology, battery energy storage systems, and smart energy management methods to provide clean and reliable electricity for EV charging. Furthermore, advancements in artificial intelligence (AI), Internet of Things (IoT), smart grids, and fast-charging technologies are improving the efficiency, reliability, and operational performance of solar-powered EV charging infrastructure. However, challenges such as high installation costs, weather dependency, battery degradation, and charging speed limitations still affect large-scale implementation. Therefore, continuous research and technological innovation are essential to improve the sustainability and effectiveness of solar-powered EV charging systems in the future. The increasing consumption of fossil fuels and rising environmental pollution have become major global concerns. Transportation systems are among the largest contributors to greenhouse gas emissions and climate change[1]–[5]. According to the International Energy Agency (IEA), the transportation sector contributes a significant percentage of global carbon dioxide emissions due to the heavy dependence on petroleum-based fuels (IEA, 2024). Rapid urbanization, industrialization, and population growth have further increased global energy demand, creating serious environmental and economic challenges. Consequently, many countries are now shifting toward renewable energy technologies and sustainable transportation systems to reduce environmental impacts and achieve long-term energy security[6]–[12]. Electric vehicles (EVs) are widely recognized as an environmentally friendly alternative to conventional internal combustion engine vehicles because they produce lower greenhouse gas emissions, reduce air pollution, and improve energy efficiency (Sovacool, 2009). EVs also help decrease dependence on fossil fuels and support the transition toward clean energy systems. Due to these advantages, governments and industries worldwide are investing heavily in EV production, charging infrastructure, and battery technologies. Policies such as carbon reduction targets, fuel economy regulations, tax incentives, and renewable energy initiatives have accelerated the adoption of EVs in many developed and developing countries[13]–[18]

The global EV market has experienced significant growth in recent years. Improvements in lithium-ion battery technology, reduced battery costs, and advancements in charging systems have increased the popularity and commercial viability of EVs[19]. However, the increasing number of electric vehicles has created a major challenge related to charging infrastructure. Reliable, accessible, and sustainable charging systems are necessary to support large-scale EV adoption and ensure efficient transportation networks[20], [21]. Most conventional EV charging stations rely on electricity generated from fossil-fuel-based power plants. Although EVs themselves produce lower direct emissions, the environmental benefits may decrease if the electricity used for charging comes from non-renewable energy sources. **Deb et al., 2018**, integrating renewable energy sources into EV charging infrastructure has become an important research and development area[9].Among different renewable energy technologies, solar energy is considered one of the most promising solutions because it is abundant, sustainable, clean, and widely available[22]–[24].

Solar-powered electric vehicle charging stations use photovoltaic (PV) systems to convert solar radiation into electrical energy for charging EV batteries. These systems help reduce greenhouse gas emissions, electricity costs, and dependence on conventional power grids. Solar-powered charging stations may operate as grid-connected systems, off-grid systems, or hybrid systems depending on the location, energy demand, and operational requirements[25]. Grid-connected systems allow energy exchange with utility grids, while off-grid systems depend mainly on solar panels and battery storage systems. Hybrid systems combine renewable energy sources with conventional grid electricity to improve reliability and operational flexibility[26]. Photovoltaic technology has improved significantly in terms of efficiency, durability, and cost reduction over the past decade. Modern PV systems can generate electricity efficiently under different environmental conditions and are increasingly being integrated into residential, commercial, and industrial applications. Solar charging stations can also be installed in parking lots, highways, public transportation stations, shopping malls, universities, and residential buildings. The integration of solar canopies in parking areas provides both electricity generation and vehicle protection from sunlight and weather conditions[9]. Battery energy storage systems are essential components of solar-powered EV charging stations because solar energy generation is intermittent and depends heavily on weather conditions and sunlight availability. Batteries store excess solar energy generated during daytime hours and provide electricity during nighttime or low-sunlight periods. Lithium-ion batteries are currently the most widely used storage technology due to their high energy density, fast charging capability, and long operational lifespan[27].However, battery degradation, thermal management, disposal issues, and high initial costs remain significant challenges[28]. Recent developments in smart charging technologies, artificial intelligence (AI), Internet of Things (IoT), and smart grid systems have improved the efficiency and reliability of solar-powered EV charging stations[6]. AI algorithms can optimize charging schedules, predict charging demand, and manage energy flow between solar panels, batteries, EVs, and utility grids. IoT technologies enable real-time monitoring of energy production, battery condition, charging status, and electricity consumption through connected sensors and communication systems. These technologies help improve operational efficiency, reduce energy losses, and support predictive maintenance. Smart grid integration is another important advancement in EV charging infrastructure. Smart grids enable two-way communication between charging stations, utility providers, and consumers. This communication allows better energy distribution, load balancing, and demand-side management. Vehicle-to-grid (V2G) technology has also emerged as a promising innovation in which EV batteries can return stored electricity back to the grid during peak demand periods[26]. V2G systems can improve grid stability, support renewable energy integration, and provide additional economic benefits to EV owners. Wireless charging technologies and ultra-fast charging systems are also gaining attention in modern EV infrastructure development. Wireless charging eliminates physical cable connections and improves user convenience through inductive power transfer systems. Fast-charging technologies significantly reduce charging time and make EVs more practical for long-distance transportation and commercial applications. However, these technologies require advanced power electronics and efficient thermal management systems. Despite the many advantages of solar-powered EV charging stations, several technical, economic, environmental, and operational challenges still limit widespread implementation. One of the major challenges is the high initial investment cost associated with solar panels, battery storage systems, power converters, and charging infrastructure[29]. In addition, solar power generation fluctuates depending on weather conditions, seasonal variations, and geographic location, which affects charging reliability and system performa[25], [30]. Energy conversion losses in PV systems, inverters, batteries, and charging equipment also reduce overall efficiency. Furthermore, large-scale charging infrastructure may create additional stress on electricity distribution networks, especially during peak charging periods. Land and space requirements for installing large solar PV systems can also be difficult in densely populated urban areas.

Developing countries face additional barriers including insufficient renewable energy policies, lack of financial support, limited technical expertise, and inadequate charging infrastructure. Public awareness regarding EV adoption and renewable energy integration also remains limited in some regions[31]. Therefore, effective government policies, financial incentives, and technological innovations are essential to support the future development of solar-powered EV charging systems[32]. Researchers are continuously exploring advanced solutions such as smart energy management systems, hybrid renewable energy systems, AI-based optimization methods, advanced battery technologies, and decentralized charging networks to overcome existing limitations[33]. The integration of renewable energy with EV charging infrastructure is expected to play a significant role in achieving global carbon neutrality and sustainable development goals in the future.

Therefore, solar-powered EV charging infrastructure is becoming an important research area for achieving sustainable transportation and renewable energy integration worldwide.

The main purpose of this review paper is to examine the technologies, operational principles, challenges, solutions, and future trends associated with solar-powered electric vehicle charging stations. The paper aims to provide a detailed overview of photovoltaic systems, battery storage technologies, smart charging methods, AI and IoT integration, and renewable energy management strategies used in EV charging infrastructure. In addition, this review discusses the major technical, economic, and environmental challenges affecting large-scale implementation and identifies possible solutions for improving system efficiency, reliability, sustainability, and future development of solar-based electric vehicle charging systems.

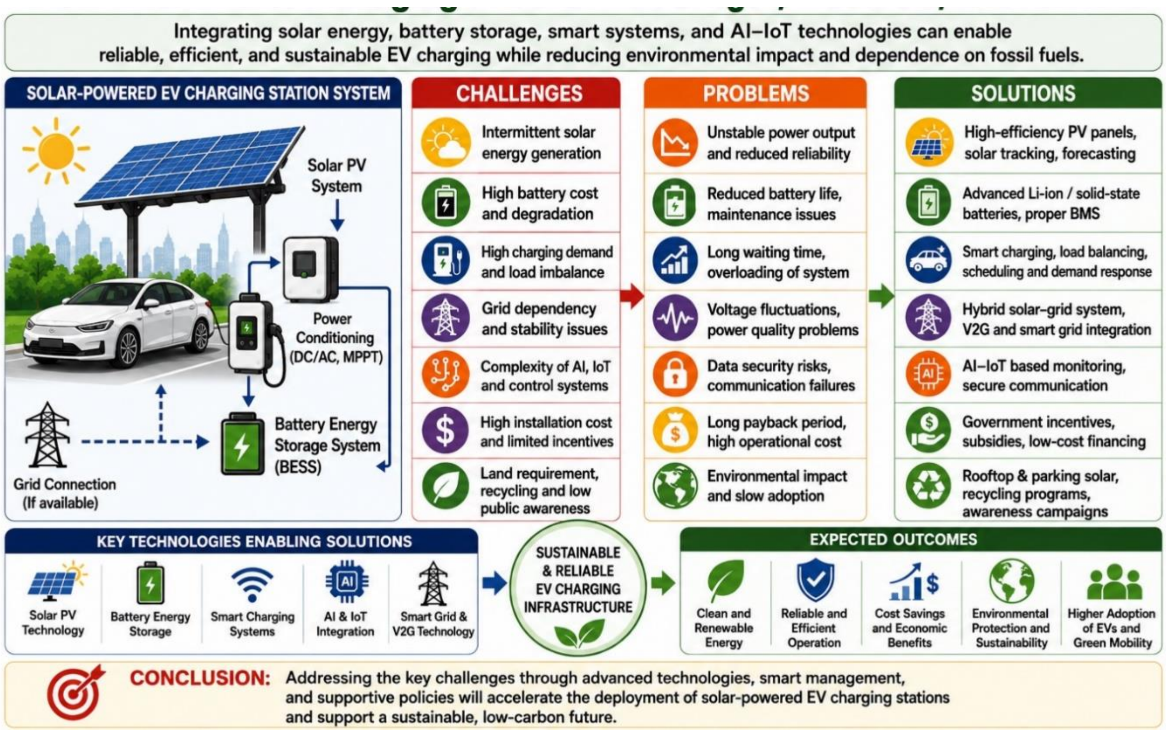


Figure 1. Solar Powered EV Charging stations

2. Technologies Used in Solar-Powered EV Charging Stations

Figure 1 presents the major technologies and operational components used in solar-powered electric vehicle charging stations. The figure illustrates how solar energy is generated, stored, managed, and supplied to electric vehicles through an integrated charging infrastructure.Solar-powered electric vehicle charging stations consist of several important technologies that work together to generate, store, manage, and deliver electrical energy to EVs. These technologies improve charging efficiency, reduce dependence on fossil fuels, and support renewable energy integration. Modern charging stations also incorporate smart communication and energy management systems to ensure reliable and sustainable operation.

2.1 Photovoltaic (PV) Systems

Photovoltaic (PV) systems are the primary source of electricity generation in solar-powered EV charging stations. PV panels convert solar radiation into electrical energy through semiconductor materials such as silicon. When sunlight strikes the surface of solar cells, electrons are released, producing direct current (DC) electricity. This electricity can either be supplied directly to EV chargers or stored in battery systems for later use.

The efficiency of PV systems depends on several factors including solar irradiance, ambient temperature, panel orientation, shading conditions, and weather variations. Proper panel alignment and installation angle are important for maximizing solar energy generation. High-efficiency monocrystalline and polycrystalline solar panels are commonly used in modern charging stations because they provide stable performance and long operational life. PV systems are environmentally friendly because they produce clean electricity without greenhouse gas emissions or air pollution. In addition, solar energy is renewable and widely available in many regions around the world. However, solar energy generation is intermittent because it depends heavily on sunlight availability and weather conditions. Therefore, additional technologies such as battery storage systems and grid connections are necessary to maintain reliable charging operations. Maximum Power Point Tracking (MPPT) controllers are also used in PV systems to improve energy conversion efficiency. MPPT controllers continuously adjust the operating point of solar panels to ensure maximum power output under changing environmental conditions.

2.2 Battery Energy Storage Systems

Battery Energy Storage Systems (BESS) are essential components of solar-powered EV charging stations because they store excess solar energy generated during daytime hours. The stored energy can later be used during nighttime, cloudy weather, or periods of high charging demand. Battery storage improves system reliability, energy stability, and charging continuity. Lithium-ion batteries are the most commonly used storage technology because of their high energy density, long life cycle, fast charging capability, and good efficiency . Other battery technologies such as lead-acid batteries, nickel-metal hydride batteries, and solid-state batteries are also being studied for EV charging applications Battery management systems (BMS) are integrated into storage systems to monitor voltage, current, temperature, state of charge, and battery health. BMS technologies help improve safety, reduce overheating risks, and extend battery lifespan. Despite their advantages, battery storage systems face several challenges including high installation cost, battery degradation, thermal management issues, and recycling concerns. Researchers are currently exploring advanced battery technologies with higher energy density, lower cost, faster charging speed, and improved safety performance.

2.3 Smart Charging Systems

Smart charging systems are designed to manage charging demand and optimize energy consumption in EV charging stations. These systems use advanced communication technologies, sensors, and software algorithms to control charging operations efficiently. Smart charging can regulate charging time, charging speed, and power distribution according to electricity demand and solar energy availability. Smart charging technologies help reduce electricity costs by charging EVs during low-demand periods or when solar power generation is high. They also minimize stress on power grids and prevent overloading problems. Load balancing techniques are commonly used to distribute electricity evenly among multiple charging vehicles.Demand response systems are another important feature of smart charging infrastructure. These systems allow charging stations to respond automatically to changes in electricity prices and grid conditions. In addition, mobile applications and cloud-based monitoring platforms allow users to monitor charging status, electricity consumption, charging cost, and battery condition in real time.Fast-charging and ultra-fast charging technologies are also integrated into modern smart charging systems. These technologies significantly reduce EV charging time and improve user convenience, especially for commercial and long-distance transportation applications.

2.4 Grid-Connected and Off-Grid Systems

Solar-powered EV charging stations can operate in grid-connected, off-grid, or hybrid configurations depending on energy demand, location, and operational requirements.

Grid-connected charging stations are connected to the main electricity grid and can obtain electricity from utility providers when solar power generation is insufficient. These systems improve charging reliability and ensure continuous operation during cloudy weather or nighttime periods. Excess solar energy can also be transferred back to the grid, improving energy efficiency and reducing electricity costs. Off-grid charging systems operate independently using only solar panels and battery storage systems. These systems are suitable for remote areas where utility grid access is unavailable or unreliable. However, off-grid systems require larger battery storage capacity and careful energy management to maintain stable operation. Hybrid systems combine solar energy, battery storage, and grid electricity to provide better operational flexibility and reliability. Hybrid charging stations are considered one of the most effective solutions because they can balance renewable energy generation with electricity demand under different environmental conditions. Vehicle-to-grid (V2G) technology is another important development in grid-connected charging systems. V2G systems allow EV batteries to return stored electricity back to the utility grid during peak demand periods. This technology can improve grid stability, support renewable energy integration, and provide economic benefits to EV owners.

2.5 Artificial Intelligence and IoT Integration

Artificial Intelligence (AI) and Internet of Things (IoT) technologies are increasingly being integrated into modern solar-powered EV charging stations to improve automation, monitoring, and energy management. AI algorithms can predict charging demand, optimize charging schedules, manage energy distribution, and improve overall system efficiency. Machine learning techniques can analyze historical charging data, weather conditions, and energy consumption patterns to make intelligent operational decisions. IoT technologies use connected sensors and communication networks to enable real-time monitoring of charging station performance. IoT sensors can measure voltage, current, battery status, solar energy production, charging activity, and environmental conditions. The collected data can be transmitted to cloud-based systems for analysis and remote monitoring. AI- and IoT-based systems also support predictive maintenance by identifying system faults and performance issues before equipment failure occurs. This reduces maintenance cost, improves system reliability, and increases operational efficiency. In addition, AI and IoT technologies improve user convenience through mobile applications, automated billing systems, smart energy management, and remote charging control. These technologies are expected to play a major role in the future development of intelligent and sustainable EV charging infrastructure.

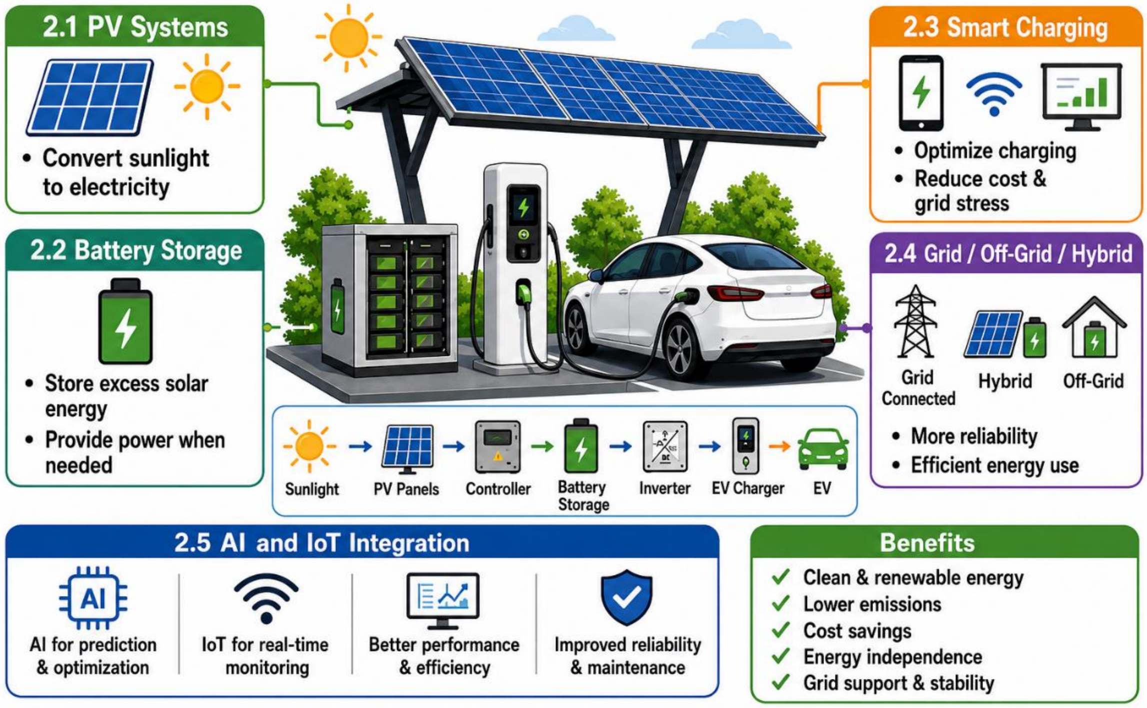


Figure 2. Technologies Used in Solar-Powered EV Charging Stations

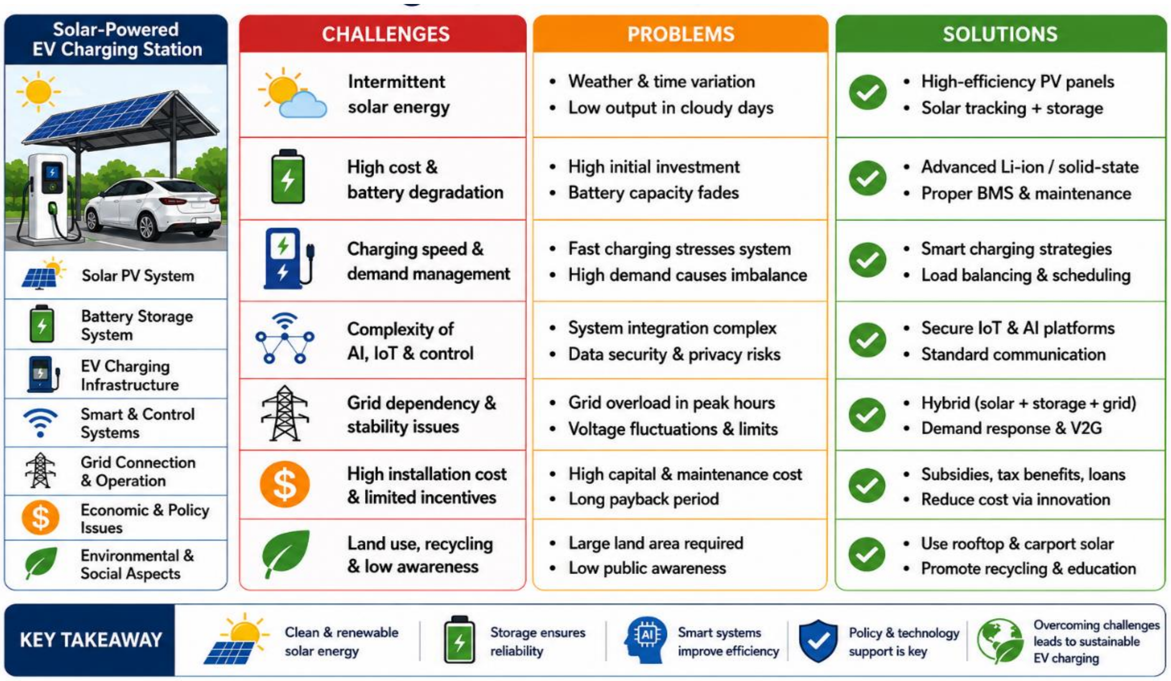
3. Challenges, Problems, and Solutions

Figure 2 and **Table 1** illustrate the major technical, economic, operational, and environmental challenges associated with solar-powered electric vehicle charging stations, along with the possible solutions used to improve system performance and reliability. The figure visually presents the relationship between different challenges, operational problems, and technological solutions, while **Table 1** summarizes these issues in a structured format for easier comparison and analysis. One of the major challenges highlighted is the intermittent nature of solar energy generation. Solar power production varies depending on weather conditions, sunlight intensity, seasonal changes, and geographical location[34]. This fluctuation can reduce charging reliability and affect continuous EV charging operations. To overcome this issue, high-efficiency photovoltaic panels, solar tracking systems, battery storage technologies, and hybrid solar-grid systems are commonly recommended[35].

Battery-related problems are also significant in solar-powered EV charging infrastructure. High battery cost, thermal management issues, limited lifespan, and battery degradation can increase maintenance requirements and operational expenses. Advanced lithium-ion batteries, solid-state battery technologies, and battery management systems (BMS) can improve battery efficiency, safety, and durability. Further identify charging demand management as another important issue. Fast charging systems can increase electricity demand and create load imbalance during peak hours. Smart charging technologies, load balancing methods, scheduling algorithms, and demand response systems are effective solutions for improving energy management and reducing stress on utility grids. Grid dependency and power stability issues are also discussed. Large-scale EV charging infrastructure may create voltage fluctuations, power quality problems, and grid overloading in densely populated areas. Hybrid charging systems, smart grid integration, and vehicle-to-grid (V2G) technologies can help improve grid stability and support efficient electricity distribution. In addition, the figure highlights the growing role of Artificial

Intelligence (AI) and Internet of Things (IoT) technologies in modern charging infrastructure. Although these technologies improve monitoring, automation, and energy optimization, they also introduce challenges related to system complexity, communication reliability, cybersecurity, and data privacy. Secure IoT platforms, standardized communication protocols, and technical training programs are important for ensuring safe and reliable system operation. Economic and environmental challenges are also presented in Figure 2 and Table 1. High capital investment, long payback periods, limited government incentives, land requirements, and battery recycling concerns continue to affect the widespread adoption of solar-powered EV charging stations. Financial support programs, policy incentives, rooftop solar installations, recycling systems, and public awareness campaigns can help address these barriers.

Overall, **Figure 2** and **Table 1** demonstrate that solar-powered EV charging stations face several interconnected challenges. However, technological advancements, intelligent energy management systems, renewable energy integration, and supportive government policies can significantly improve system efficiency, reliability, sustainability, and long-term implementation.



Solar-Powered EV Charging Station

Solar-Powered EV Charging Station	CHALLENGES	PROBLEMS	SOLUTIONS
Solar PV System	Intermittent solar energy	• Weather & time variation • Low output in cloudy days	• High-efficiency PV panels • Solar tracking + storage
Battery Storage System	High cost & battery degradation	• High initial investment • Battery capacity fades	• Advanced Li-ion / solid-state • Proper BMS & maintenance
EV Charging Infrastructure	Charging speed & demand management	• Fast charging stresses system • High demand causes imbalance	• Smart charging strategies • Load balancing & scheduling
Smart & Control Systems	Complexity of AI, IoT & control	• System integration complex • Data security & privacy risks	• Secure IoT & AI platforms • Standard communication
Grid Connection & Operation	Grid dependency & stability issues	• Grid overload in peak hours • Voltage fluctuations & limits	• Hybrid (solar + storage + grid) • Demand response & V2G
Economic & Policy Issues	High installation cost & limited incentives	• High capital & maintenance cost • Long payback period	• Subsidies, tax benefits, loans • Reduce cost via innovation
Environmental & Social Aspects	Land use, recycling & low awareness	• Large land area required • Low public awareness	• Use rooftop & carport solar • Promote recycling & education

KEY TAKEAWAY: Clean & renewable solar energy | Storage ensures reliability | Smart systems improve efficiency | Policy & technology support is key | Overcoming challenges leads to sustainable EV charging

Figure 3. Challenges, Problems, and Solutions

Challenges/Problems	Description	Possible Solutions
High Installation Cost	Solar panels, batteries, and charging infrastructure require large initial investment (Yilmaz & Krein, 2013).	Government incentives, subsidies, and low-cost PV technologies.
Weather Dependency	Solar energy generation decreases during cloudy or rainy weather (Liu et al., 2015).	Hybrid systems with battery storage and grid support.
Battery Storage Limitations	Batteries are expensive and degrade over time (Ahmad et al., 2020).	Development of solid-state and advanced lithium-ion batteries.

Slow Charging Speed	Charging may become slow during low solar generation periods.	Fast DC chargers and smart charging technologies.
Grid Stability Issues	Large-scale EV charging can increase load on power systems (Shareef et al., 2016).	Smart grid integration and demand management systems.
Space Requirements	Large PV systems require considerable installation area.	Solar parking canopies and compact panel technologies.
Maintenance and Reliability	PV panels and batteries require regular maintenance.	IoT-based monitoring and predictive maintenance systems.
Energy Conversion Losses	Conversion losses reduce system efficiency.	High-efficiency converters and MPPT controllers.

Solar-powered EV charging stations combine solar generation, charging hardware, and often storage and grid links to charge vehicles with cleaner electricity. They are gaining attention because they can cut emissions, lower peak grid demand, and support charging in both cities and remote areas. Solar-powered electric vehicle charging stations use photovoltaic panels to generate electricity for EV charging, either in real time or with help from batteries and the grid when solar output changes. In simple forms, they include PV panels, power conversion units, EV chargers, and control systems; in more advanced forms, they also include battery storage, smart energy management, and grid or building links. Interest in these systems has grown with the rise of EV adoption, concerns about the emissions tied to fossil-fuel-based grids, and the need to avoid adding large new loads to already stressed power networks. They are now studied and deployed as standalone off-grid systems, grid-connected stations, and hybrid designs that balance solar use, charging demand, cost, and reliability. A useful review therefore needs to cover not only hardware and charging types, but also energy control, grid interaction, economics, deployment evidence, current limits, and likely next steps in research and practice.

4. Results and Discussion

The review of previous studies shows that solar-powered EV charging stations provide significant environmental and economic benefits compared with conventional charging systems. These systems reduce greenhouse gas emissions and support the use of renewable energy in transportation sectors[32]. Most research findings indicate that grid-connected solar charging systems are more reliable than completely off-grid systems because they can continue operating during low solar radiation periods[9]. Hybrid systems that combine solar energy, battery storage, and grid electricity offer improved stability and energy security.

Battery energy storage systems play an important role in maintaining continuous charging operations. Lithium-ion batteries are currently the most widely used storage technology because of their high efficiency and energy density. However, battery cost and lifespan remain important concerns for long-term implementation. Recent advancements in AI and IoT technologies have significantly improved energy management in solar EV charging stations. AI-based systems can predict charging demand, optimize power distribution, and improve charging efficiency. IoT monitoring systems allow real-time tracking of system performance, battery condition, and energy usage. Vehicle-to-grid (V2G) technology has also emerged as a promising future solution. In V2G systems, EV batteries can send electricity back to the grid during peak demand periods, improving grid stability and energy management[19]. Although many benefits have been achieved, several barriers still limit widespread adoption. High installation costs, weather dependency, lack of charging infrastructure, and limited public awareness remain major challenges, especially in developing countries. Researchers suggest that future work should focus on reducing system costs, improving battery technology, and increasing charging efficiency. Solar-powered EV charging stations combine solar generation, charging hardware, and often storage and grid links to charge vehicles with cleaner electricity. They are gaining attention because they can cut emissions, lower peak grid demand, and support charging in both cities and remote areas. In practice, solar EV charging stations are not one fixed design but a family of architectures built around PV generation, power conversion, charging hardware, and sometimes storage, grid links, or other renewable sources. A notable review describes this area in terms of different solar PV charging technologies, charging standards, and charging modes, showing that both hardware design and charging method are central to station design choices[36]. A common high-level split is between photovoltaic grid-connected charging and photovoltaic standalone charging[37]. In grid-connected systems, EVs can draw from solar when available and from the utility when PV output is low, which makes this layout attractive for places such as workplace parking and other urban sites[11]. In standalone or off-grid systems, the station depends mainly on local PV and therefore usually needs energy storage to keep charging reliable when sunlight changes or disappears. Some recent summaries reduce this to two basic configurations and stress the same design goal: maximize PV use for EV charging while minimizing grid use[38].

A widely studied architecture is the PV-storage charging station, which extends a traditional charging site by adding both PV generation and an energy storage system. In this form, the station acts like a microgrid that integrates source, storage, and load, allowing better on-site use of renewable generation and helping reduce the stress that charging places on the local distribution network[30]. This source-storage-load view also appears in many prototype designs that combine solar panels, charge controllers, batteries, DC-DC converters, and coordinated control to manage power between PV, storage, the grid, and connected vehicles [39]. In homes or apartment buildings with limited grid connection, local battery packs can also let stations offer semi-fast or fast charging without exceeding the site's grid power limit[10]. More broadly, coordinated PV-plus-grid operation through a shared DC bus is often presented as a practical large-scale option because it allows smooth switching between solar-fed and grid-fed mode[40], [41]. Beyond these core layouts, several papers point to hybrid renewable architectures. These combine solar with wind, storage, and smart-grid functions so the station can keep charging when one renewable source is weak and can distribute power across multiple EVs more flexibly[42], [43]. Other variants add fuel cells and electrolyzers as backup or balancing resources, again showing that PV-only charging is only one point in a wider design space of renewable EV charging stations[44]. Deployment form also matters: PV can be mounted on rooftops over buildings or parking lots, on solar carports, or integrated into broader urban assets such as streetlight networks that route surplus solar energy to shared batteries and chargers[44]–[46].

Charging technology itself also varies. A common distinction is between charging while the vehicle is parked and charging while driving. Parked charging includes conventional conductive AC and DC charging, with stations sometimes designed to support both slow and fast modes depending on converter size, storage support, and grid access[10], [43]. Several recent works also explore wireless power transfer, where solar-fed DC buses and converters drive high-frequency inverter stages and resonant couplers to transfer energy without plugs[12], [47]–[49]. Reviews of this area note that wireless charging now forms an important branch of solar charging station research, including work on coil structures, compensation networks, and AI-assisted control[50]. A related but more specialized path is vehicle-integrated photovoltaics, where PV modules are mounted directly on the vehicle body so the EV can gain some energy while parked or moving, though this is usually a supplement rather than a full substitute for station-based charging[31] Across these architectures, a repeated design pattern is the use of MPPT-enabled PV conversion, battery storage for buffering, and modular converter-based interfaces that make the station adaptable to local conditions and charging rates[7]. Recent work also suggests that future stations will be more digital and modular, with mobile apps, IoT links, and multiport power converters added on top of the basic PV-charger architecture[3], [33]. Overall, the technology trend is clear: solar EV charging stations are moving from simple PV-fed chargers toward hybrid, storage-backed, and communication-rich systems that can support different charging speeds, site types, and user needs.Solar-powered EV charging stations show strong potential for supporting sustainable transportation systems and achieving global clean energy goals[51].

4.1. Benefits, feasibility, and deployment evidence

Solar-powered EV charging stations can cut emissions, lower charging and operating costs, reduce grid stress, and support charging where grid supply is weak. Real-world studies and deployments suggest they are already feasible in many settings, especially when paired with storage or grid backup, though performance still depends strongly on local solar conditions, costs, and charging demand. The literature is broadly consistent that solar-powered EV charging stations offer three main benefits: cleaner charging, less pressure on the grid, and a path to more self-supplied mobility energy. Reviews note that these systems can reduce greenhouse gas emissions, lower charging costs, and weaken the impact of EV charging on local distribution networks, which is especially important as EV adoption rises[28], [52]. More recent summaries also frame them as a practical way to reduce fossil-fuel dependence in transport by using PV energy as much as possible and minimizing grid electricity use[53]. In PV-storage forms, the benefit is not only cleaner charging but also better local power balancing: on-site solar generation plus storage can absorb part of the charging load and reduce strain on the regional grid[54], [55]. Feasibility depends on site conditions, demand patterns, and whether the station has storage or grid support, but the evidence is increasingly positive. A notable review by Khan et al. explicitly examined feasibility, economic analysis, deployment, and sustainability across solar PV-EV charging technologies, showing that feasibility is now discussed as a practical design and planning question rather than only a conceptual one[36]. Ye et al. summarize studies ranging from remote-area charging to PV microgrids and techno-economic analysis, and report prior work that regarded PV-powered EVs as among the most promising near-term supply models while also noting the value of storage to avoid wasting surplus renewable electricity[28]. More recent reviews reach a similar conclusion: PV systems over homes, buildings, and parking lots are presented as feasible and efficient charging solutions, provided technical constraints are managed and the technology continues to improve[44]. At the same time, authors are careful not to overstate this point. Profitability is possible, but limited PV area, limited battery capacity, and variable solar output can make some systems less cost-effective if they are poorly sized or if demand is too high relative to renewable supply[11]. Deployment evidence also shows that these systems are no longer rare prototypes. Liu et al. report that large-scale solar-powered EV charging stations have already been built in countries such as the United States, the United Kingdom, the Netherlands, and Malaysia, and that China has launched PV-storage charging demonstration projects in Dongguan, Shanghai, and Qingdao[30]. Other reviews point to real-world deployment in parking lots, shaded car parks, rooftops, and hybrid renewable projects, indicating that the concept is being adapted to both urban and distributed settings[56]. There is also evidence for integration into existing infrastructure rather than only purpose-built sites, such as using solar streetlight networks to collect surplus energy into shared batteries that then serve EV chargers[46]. Economic and environmental case studies strengthen the deployment argument. Fakour et al. report a case study with about 140 MWh/year of solar yield, enough to provide solar electricity for more than 3000 vehicles per month with one-hour parking, while cutting total carbon dioxide emissions by 94% relative to conventional grid electricity; they also find that the business case improves under higher carbon tax assumptions[4]. Almasri et al. compile techno-economic results from prior studies and report on-grid energy costs spanning USD 0.0032 to 0.5645 per kWh, with payback periods ranging from 1 to 15 years, which suggests that many projects can be financially reasonable depending on location and design. These numbers vary widely, but that variation itself is useful evidence: station performance is highly site-specific, and good feasibility assessment must include local irradiance, land or roof area, charging demand, tariffs, storage sizing, and policy incentives[6].

The literature also shows that solar charging can expand access, not just improve environmental performance. Earlier studies highlighted renewable charging as a way to serve rural and isolated areas far from strong grids[28]. Recent work extends that idea to decentralized and resilient energy systems, arguing that wider use of PV-powered EV charging can support more robust local energy networks and green mobility at the same time[57]. Hybrid solar-wind and smart-grid-linked charging projects similarly suggest that deployment can be tailored to local resources and can help support low-emission transport in different geographic setting[41].A practical reading of the evidence is that solar EV charging is feasible today, but usually not as a PV-only system sized in isolation. Several sources stress that daytime-only generation and uncertainty in solar output limit how much demand can be covered directly, so a battery bank or grid connection is commonly needed for dependable operation[5], [11]. Even studies focused on novel options such as wireless solar charging and solar-fed smart stations describe feasibility as conditional on local design choices, technology maturity, and ongoing improvements in storage, converters, and digital control[58]. Overall, the deployment record and case-study results support a clear conclusion: solar-powered EV charging stations already work in real settings and can deliver strong environmental and grid benefits, but their best performance comes from careful sizing, hybridization, and matching the station design to the local solar resource and user demand.

4.2. Energy management, control, and grid interaction

The main control task in a solar EV charging station is to decide, in real time, how much power should come from PV, batteries, the grid, and sometimes the vehicles themselves. Good energy management can raise solar use, lower charging cost, reduce peak stress on the grid, and make charging more reliable despite the variable nature of solar power.

Energy management is what turns a solar-powered charging station from a simple PV-fed charger into a workable power system. In most designs, the controller must balance four flows at once: PV generation, battery charging and discharging, EV charging demand, and grid import or export. Several papers therefore frame the station as a coordinated PV-battery-grid-EV system rather than a standalone charger, and they propose real-time strategies to schedule charging, absorb solar variability, and reduce operating cost. For example, Xiong et al. describe a real-time energy management strategy for a commercial-area PV EV station that coordinates PV generation, battery packs, the energy management system, and charging devices so vehicles can be charged in an orderly way while making full use of solar energy and reducing cost[59]. Similar control goals appear in later system studies that use MPPT, PID, and current control to manage power among solar, battery storage, the grid, and EVs while avoiding unnecessary burden on the utility network[39]. More recent EMS descriptions make this logic explicit: charge EVs directly from PV when possible, store excess solar in a battery, then use that stored energy later when irradiance is low or electricity prices are high, using real-time inputs such as irradiance, battery state of charge, price signals, and EV charging needs to schedule power flows[54]. Because solar output is uncertain and concentrated in daytime hours, most papers treat storage or grid support as necessary rather than optional for dependable service. Reviews note that while solar charging can cut greenhouse gas emissions, charging cost, and added grid load, the intermittency of PV means that a grid connection or battery bank is usually needed for effective station operation[52]. Ye et al. also organize prior work around this same problem: some studies use renewable charging to serve remote areas far from strong grids, others aim to reduce local grid overload from EV charging, and another group explores V2G-based interaction with the local grid, while warning that intermittency and uncontrolled charging or discharging can create reliability and security risks[28]. In practical home and apartment settings, local battery packs are often used to overcome limited grid connection capacity and still provide semi-fast or fast charging, which shows how control and storage can substitute for a weak service connection at the site level[10]. Grid interaction is therefore a core part of control design. A common operating approach is multimode control, where the station runs on solar when available and shifts to the grid when needed, often through a shared DC bus with bidirectional converters. Yadnik et al. emphasize that the quality of control is judged by how smoothly the station transitions between solar-connected and grid-connected modes, especially during peak-load hours when coordinated operation can improve grid stability and make large-scale deployment more economical[40]. More broadly, reviews of EV/PV integration conclude that PV-grid charging can be profitable, but only when the power management strategy deals well with limited PV and battery capacity and with times when consumer demand exceeds local renewable supply[11]. Some newer optimization frameworks go further by using solar forecasts and probabilistic EV arrival predictions so the station can decide in advance when to charge batteries, import from the grid, or export surplus power, which improves both commercial viability and grid resilience[5].

Another important control trend is to treat the charging station as part of a smart grid or microgrid rather than as an isolated load. Hybrid renewable charging stations are being designed with smart-grid functions that distribute power among multiple EVs according to demand, renewable availability, and grid conditions[42]. Related reviews highlight predictive analytics, real-time adjustment, adaptive converter control, and smart-grid support as key tools for handling energy variability and keeping the power flow stable and efficient from PV panels to EV batteries[57]. In this broader grid-aware view, EVs themselves may also act as flexible resources through bidirectional charging. V2G can help with peak load management, frequency regulation, and microgrid stability, but its value depends on having enough plugged-in vehicles available at the right time, and that mobility constraint makes EVs less predictable than fixed storage[1], [49].That is why many papers present V2G as promising but operationally more complex than simply adding a stationary battery. Control research also increasingly depends on power-electronic architecture and digital communication. Multiport converter designs are being studied because they can integrate several sources and loads more efficiently, especially where medium-voltage or high-power fast charging is involved, but they also require stronger control algorithms for adverse grid conditions and add implementation complexity. At the system level, newer concepts also include user-facing digital layers such as mobile apps, real-time billing, and usage history, which do not manage power directly but help align charging behavior with available solar energy and storage conditions[3]. IoT-enabled charging systems extend this trend by linking sensing, communication, and control, though they also introduce new concerns around cybersecurity, energy optimization, and overall system complexity[60].

Overall, the literature shows a clear shift from static PV-fed charging to predictive, coordinated, and grid-aware control. The best-performing concepts are not those that rely on solar alone, but those that combine PV, storage, flexible charging schedules, converter-level control, and managed grid interaction so the station can use as much renewable energy as possible without sacrificing reliability, economics, or local power quality.

4.3. Challenges and limitations

The biggest limits of solar-powered EV charging stations come from mismatch: solar output changes with time and weather, while EV users want fast, reliable charging whenever they arrive. On top of that, high upfront cost, battery and converter constraints, siting needs, grid integration issues, standards gaps, and digital-security concerns all make design and scale-up harder.A central challenge is that solar generation and charging demand do not naturally line up. Solar power is variable, uncertain, and concentrated in daytime hours, so it often cannot meet charging demand at the exact time users need energy; several reviews therefore note that battery storage or a grid link is usually needed to keep service reliable[26], [36], [46]. This same issue appears at the component level: storage must be sized well enough to sustain variable loads, but batteries add cost, age over time, and still have finite capacity, which can make some PV-grid systems less cost-effective than expected if PV area and storage are too small for local demand (Enescu et al., 2023)(Alrubaie et al., 2023). Liu et al. describe PV-storage charging stations as promising source-storage-load microgrids, but explicitly note that there are still many challenges in their planning process, underscoring that adding storage helps rather than eliminates design difficulty (Liu et al., 2020).

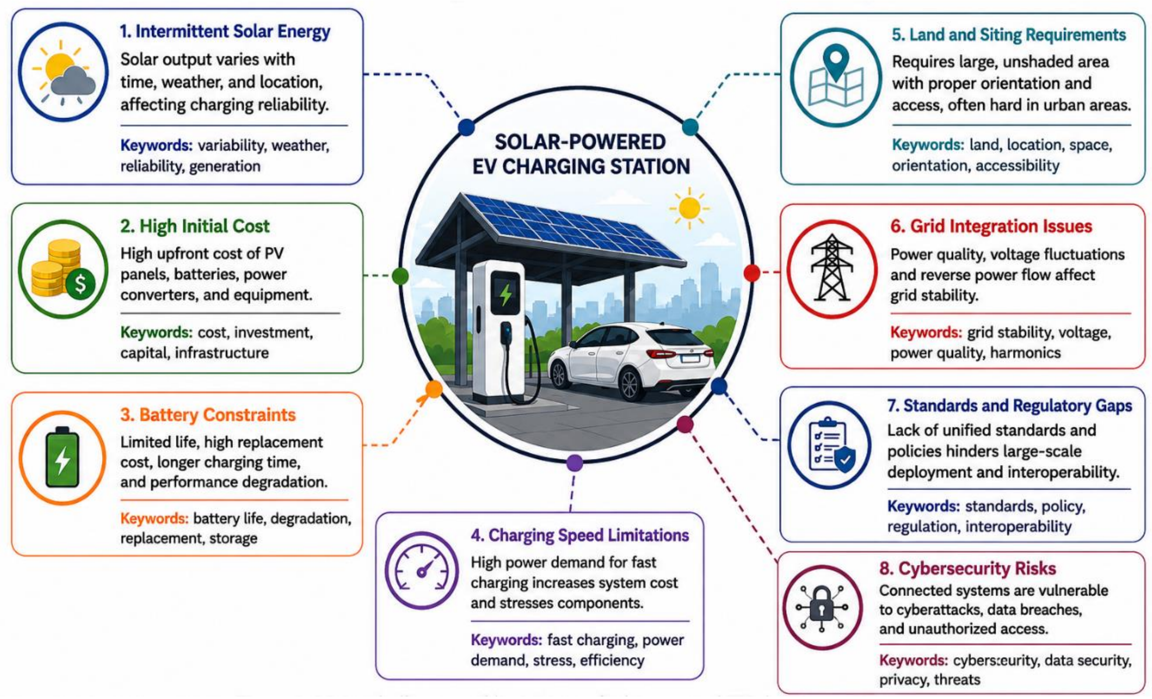


Figure 4. Major Challenges and Limitations of solar poweres EV charging

A second major limitation is service quality from the user side: EV drivers care about charging time, driving range, and station access. Haritha et al. note that long charging time, battery lifetime concerns, range anxiety, and the need for easily accessible charging infrastructure remain basic barriers to wider EV use, even when solar is added[55]. Ramadan et al. similarly point to limited charging speed and the need for additional infrastructure, showing that solar power does not by itself solve the fast-charging problem[53]. In practice, if a site is expected to offer high-power or fast charging, it usually needs larger converters, stronger grid support, larger batteries, or all three, which raises cost and system complexity[61].Cost and site dependence are also persistent limits. A notable review by Khan et al. includes roadblocks, challenges, and sustainability alongside feasibility, reflecting that economics remain a first-order issue in deployment planning[36]. Later papers make this concrete: PV systems can have high initial cost, and their feasibility depends strongly on local conditions such as sunlight, weather, and system design[47]. Haritha et al. add that the station should be located in areas with good solar irradiance, which means that land availability, shading, and local geography directly shape what is practical. Guo et al. further note that PV performance can drop because of shading, dust, and temperature changes, so even well-sited systems may underperform without maintenance and careful design[51].Power-electronic and grid-integration challenges form another important set of limits. Lalitha et al. point to the need for high-efficiency converters that can operate well under changing solar conditions, along with adaptive control to keep power flow stable from the PV side to the EV battery side. As stations become larger and more flexible, bidirectional power flow and vehicle-grid interaction can support peak shaving and frequency regulation, but they also require the grid and control architecture to handle added complexity safely[57]. Suvvala et al. make a similar point for multiport converter-based stations: they can improve efficiency and flexibility, especially in higher-power settings, but they need more robust control under adverse grid conditions and are harder to implement simply[61]. More broadly, EV charging and grid interconnection standards, communication architectures, and grid effects remain a live infrastructure challenge rather than a solved problem[62]. There are also system-level barriers around interoperability, scale, and regulation. Tejeida-Padilla et al. highlight regulatory and policy barriers that hinder interoperability between charging stations and vehicles from different manufacturers, and call for greater global standardization[63].That matters for solar-powered stations because they sit at the intersection of EV hardware, grid codes, communications, and renewable-energy equipment. Without common standards, it is harder to deploy systems that are easy to connect, maintain, upgrade, and use across different markets. Newer charging forms add their own limits rather than removing old ones. Wireless solar charging is attractive for convenience, but current papers still frame it as an area with unresolved efficiency, storage, and variability issues, as well as a need for more research and development before broad rollout. Some prototype-oriented papers also mention heating during charging, charging depletion concerns, and high installation cost in wireless station concepts[12], [48], [64].

Finally, as stations become smarter, digitalization creates another layer of risk. IoT-enabled solar charging can improve monitoring and control, but it also brings challenges in cybersecurity, energy optimization, and overall system complexity. likewise point to cybersecurity and implementation simplicity as open issues in advanced converter-rich charging systems. Taken together, the literature suggests that the core challenge is no longer proving that solar EV charging can work, but making it work reliably, affordably, securely, and at scale across very different sites and operating conditions.

4.4. Future trends and research directions

Future solar EV charging stations will likely become more hybrid, more storage-backed, and more digitally managed. Research is moving toward smarter control, faster and more flexible charging, stronger grid support, better power electronics, and wider standardization so these stations can scale reliably. A clear future direction is the continued shift from simple PV-fed chargers to PV-storage charging microgrids that coordinate solar generation, storage, charging loads, and the grid as one system. Several papers suggest that deployment should grow as PV-storage technology improves and costs fall, although planning and sizing will remain important research problems[48], [50]. Future work is therefore likely to focus less on proving the concept and more on designing stations that can deliver high renewable use, reliable service, and low grid impact at scale.

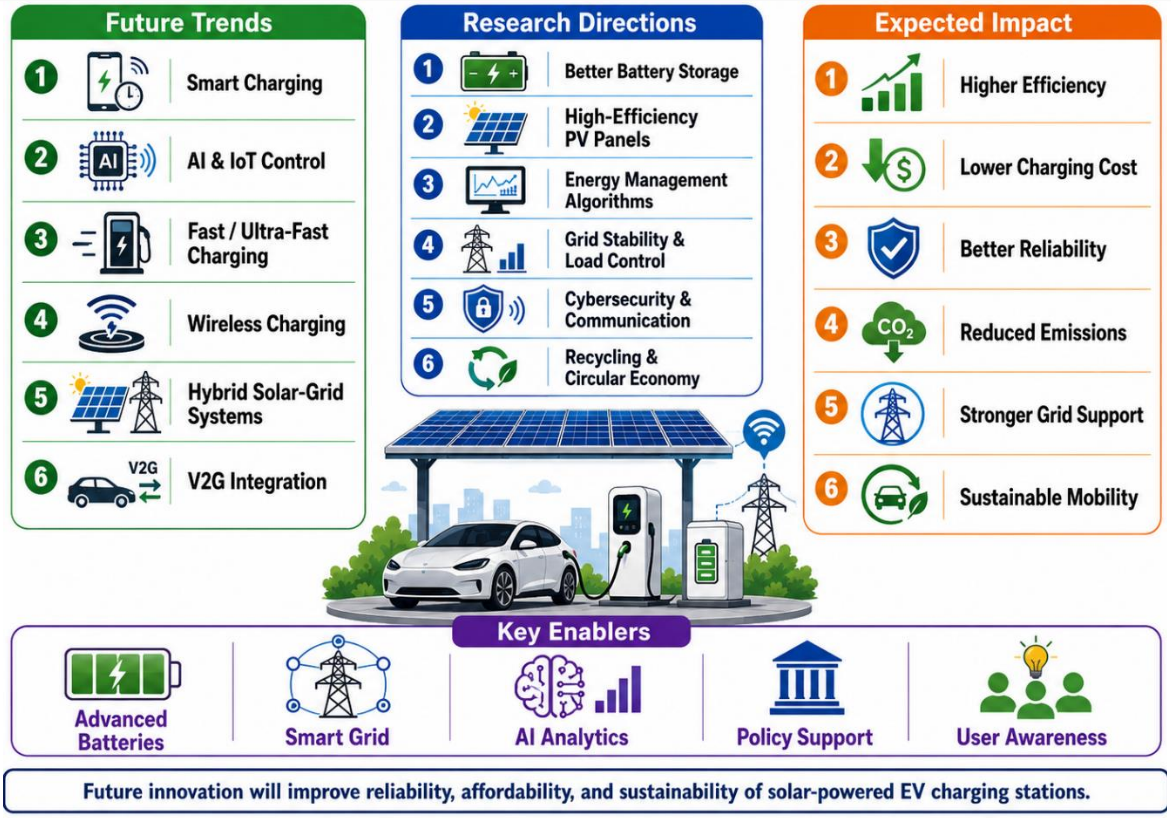


Figure 5 Future trend and research directions

Another major trend is hybridization. Instead of relying on solar alone, newer station concepts combine solar with wind, batteries, and emergency grid support to provide more stable charging[65]. This is especially relevant where weather is variable, demand is uncertain, or uninterrupted service is required. Studies on hybrid renewable charging stations present this as a practical path to clean, reliable, and cost-effective charging, supported by smart-grid coordination and better power sharing among vehicles. Control and forecasting will also become more important. Recent work points toward predictive analytics, real-time adjustment, and advanced energy management across the full chain from PV panels to EV batteries. In practice, this means using forecasts, charging behavior, battery state, and grid conditions to decide when to charge vehicles, charge storage, or exchange power with the grid. These methods are likely to be central to improving both reliability and economics in future stations. More broadly, digital tools such as IoT connectivity, communication modules, and app-based user interfaces are likely to become standard parts of station operation, not just optional extras[66]. Power-electronic design is another active research path. Future stations are expected to use higher-efficiency converters, adaptive converter control, and in some cases multiport converter architectures that can connect PV, storage, the grid, and chargers more flexibly. This matters most for medium-voltage sites, high-power charging, and systems that need to operate well under changing solar and grid conditions. At the same time, the literature makes clear that these gains depend on better control robustness, simpler implementations, and stronger cybersecurity protections. Charging technology itself is also expanding. Future station designs are likely to support a wider mix of AC, DC, wireless, and ultra-fast charging rather than a single charging mode. Wireless power transfer is a particularly visible research area, with work on solar-fed wireless charging systems, coil structures, compensation networks, and AI-assisted efficiency improvement. This suggests that convenience-focused charging may become a more important part of solar charging research, especially in controlled parking environments. Continued gains in solar panel efficiency and battery technology should also help address current limits on charging speed and energy availability[67]–[70].

A further research direction is deeper grid interaction. Bidirectional charging and vehicle-to-grid operation are increasingly treated as future enablers for peak shaving, frequency regulation, and local energy balancing, but they require smarter grid infrastructure and control frameworks that can safely handle bidirectional flows. This points to future work not only on station design but also on how utilities, aggregators, and charging operators coordinate flexible EV loads and mobile storage resources. The same logic connects to broader policy and market design: tariff design, carbon-aware charging, and orderly charging strategies can shape how economically attractive and grid-friendly these stations become.

Finally, future progress will depend not only on engineering but also on standardization, economics, and deployment practice. Reviews highlight the need for greater interoperability between chargers and vehicles from different manufacturers, as well as policy support that can reduce friction in deployment and encourage scale-up. Economic evidence already suggests that PV-powered charging can be viable in many cases, with payback periods often within practical ranges, so future work will likely focus on making those results more consistent across locations through better siting, design tools, and business models. Taken together, the literature points to a future in which solar-powered EV charging stations are more decentralized, more intelligent, and more integrated with both users and the grid, but also more dependent on advances in control, interoperability, security, and system-level planning.

4.5 Environmental Sustainability and Recycling

Environmental sustainability is an important part of solar-powered electric vehicle charging stations because these systems depend on solar panels, batteries, power converters, and charging equipment. Although solar EV charging stations reduce greenhouse gas emissions and fossil fuel dependence, they also create environmental concerns at the end of equipment life. EV batteries and solar panels contain valuable materials that should be recovered instead of being disposed of as waste.

EV batteries usually contain materials such as lithium, cobalt, nickel, copper, and aluminum. These materials are expensive and require mining, which can create environmental and social impacts. Recycling used batteries helps recover these valuable materials and reduces the need for new raw material extraction. It also lowers the amount of hazardous waste entering landfills. Proper battery recycling is especially important because battery degradation and replacement are major issues in EV charging systems. Solar panels also need proper recycling after their service life. Old or damaged photovoltaic panels may contain glass, aluminum, silicon, and other recoverable materials. If these panels are not recycled properly, they may contribute to electronic waste. Recycling solar panels can reduce waste, save natural resources, and support the circular economy. This means that materials from old solar panels can be reused in new energy technologies instead of being discarded. **Figure 3** shows the recycling process of EV batteries and solar panels. The process includes collection, sorting, dismantling, material recovery, and reuse. The figure also highlights important recovered materials such as lithium, cobalt, nickel, aluminum, glass, and silicon. These materials can be reused in the production of new batteries, solar panels, and other clean energy components.

Recycling also improves the long-term sustainability of solar-powered EV charging infrastructure. It reduces pollution, supports resource recovery, and lowers the environmental footprint of renewable energy systems. In addition, recycling programs can create economic opportunities by developing new industries related to battery processing, solar panel recovery, and material reuse. However, recycling still faces several challenges. These include high recycling costs, lack of collection systems, limited recycling facilities, and insufficient public awareness. In many developing countries, recycling olicies and technical infrastructure are still weak. Therefore, governments, industries, and researchers should work together to develop effective recycling systems, safety standards, and public awareness programs.

Overall, environmental sustainability does not only depend on using solar energy for EV charging. It also requires responsible management of batteries, solar panels, and electronic components after their useful life. Recycling and reuse can make solar-powered EV charging stations more sustainable, affordable, and environmentally friendly in the long term.

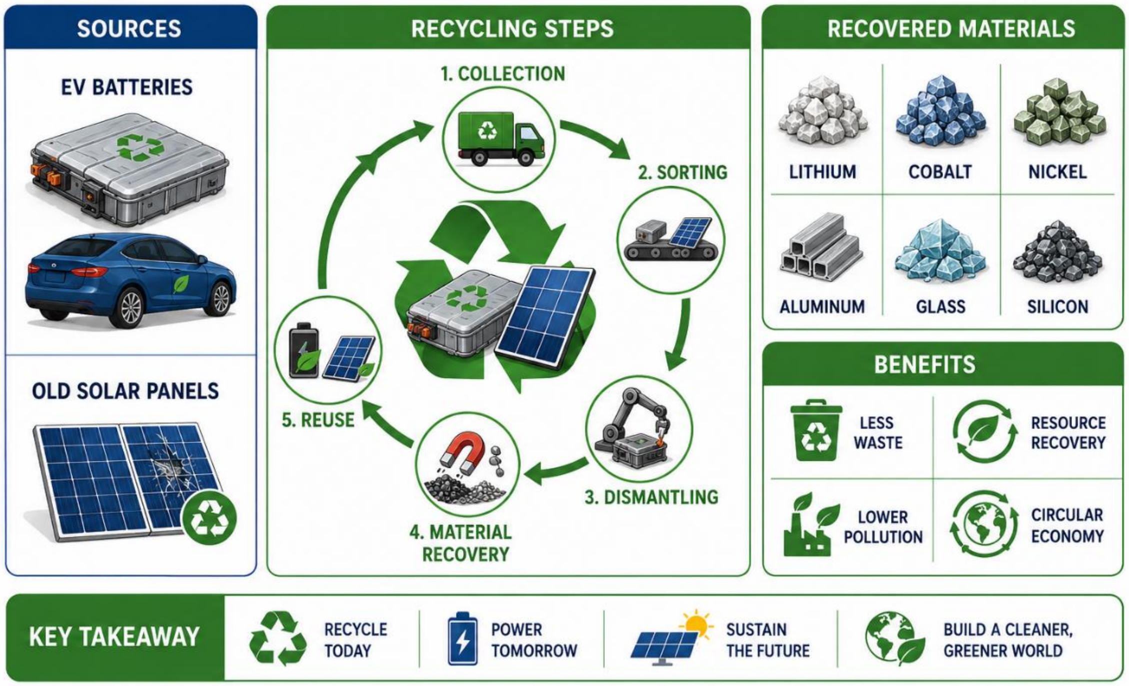


Figure 6. Recycling of EV Batteries and Solar Panels

5. Conclusion

1) Solar-powered electric vehicle charging stations represent an important solution for future sustainable transportation systems. The integration of solar photovoltaic technology with EV charging infrastructure can reduce greenhouse gas emissions, dependence on fossil fuels, and electricity costs. This review paper examined the technologies, challenges, solutions, and future trends associated with solar-powered EV charging systems.
2) The study found that smart charging systems, battery energy storage technologies, AI-based energy management, and IoT monitoring can significantly improve system performance and reliability. However, several challenges such as high installation cost, weather dependency, battery degradation, and charging speed limitations continue to affect large-scale implementation.
3) The increasing demand for clean transportation and renewable energy is expected to accelerate the development of solar-powered charging infrastructure worldwide. Continued research and technological improvements will be necessary to overcome existing challenges and ensure long-term sustainability.

6. Recommendations

1) Governments should provide financial incentives and subsidies for renewable EV charging infrastructure.

2) Researchers should focus on developing low-cost and high-efficiency solar panels.
3) Advanced battery technologies such as solid-state batteries should be further explored.
4) AI and IoT-based smart energy management systems should be integrated into charging stations.
5) More investment should be made in fast-charging solar systems.
6) Hybrid charging systems combining solar and grid power should be encouraged for better reliability.
7) Public awareness programs should be conducted to promote sustainable transportation.
8) Future studies should focus on vehicle-to-grid (V2G) technology and smart grid integration.

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