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SMART INTEGRATION OF SOLAR PV IN ELECTRIC VEHICLE CHARGING NETWORKS: TECHNO-ECONOMIC FEASIBILITY AND ENVIRONMENTAL IMPACT

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Abstract

As the need for sustainable transportation increases, there is a growing interest in using solar photovoltaic (PV) systems for charging electric vehicles (EVs). This review looks at the technical, economic, and environmental factors of solar-powered EV charging systems, pointing out their benefits, challenges, and possibilities for widespread use. A major focus is on using flexible, low-cost thin-film solar cells that can be built into the surfaces of vehicles and charging stations. This approach helps improve energy independence and adaptability. Adding solar PV to EV charging stations has several advantages, such as reducing reliance on traditional electricity sources, lowering greenhouse gas emissions, and encouraging the use of renewable energy. The study examines different system setups—grid-connected, off-grid, and hybrid—across various weather and operational conditions. The findings indicate that these systems can lower the demand on the power grid, reduce worries about running out of charge, and save money in the long run, despite high initial costs. Environmental studies show a significant decrease in carbon emissions. However, challenges like the unpredictability of solar energy, the need for energy storage, and how to connect with existing power systems still need to be addressed. The paper calls for collaboration among researchers, policymakers, and industry leaders, emphasizing that smart planning, innovative technologies, and supportive policies are crucial for developing a reliable, eco-friendly, and cost-effective solar-powered EV charging system.

Introduction:

The fast growth of electric vehicles (EVs) is changing the transportation industry. This change is driven by new technology, concerns about the environment, and supportive government policies, leading to more people choosing EVs over traditional gas-powered cars [1][2][3]. EVs help reduce our dependence on fossil fuels and lower greenhouse gas emissions [4][5][6]. They also have benefits like being quieter, needing less maintenance, and providing a better driving experience [2][6].

A key part of this transformation is using renewable energy, especially solar power, for charging EVs. Solar-powered charging stations can further reduce emissions and promote sustainable energy use [4][7][5]. Using flexible thin-film solar cells and decentralized solar

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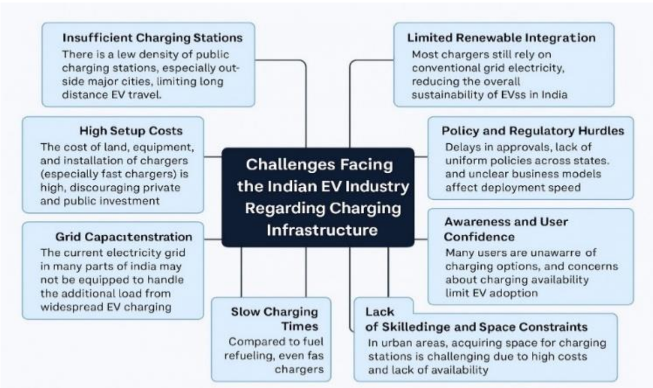
systems allows for charging options that don't rely on the electrical grid, which is helpful in remote areas where power lines are lacking [4][8].

However, there are still challenges to overcome, such as the high costs of installation and the technical complexities involved [4][7]. We need to address issues like connecting these systems to the existing power grid, the unpredictable nature of solar energy, and ensuring compatibility with current charging infrastructure, which still mostly relies on traditional electricity sources [7] [5][8].

Our research highlights the importance of pairing EVs with renewable energy to achieve greater sustainability. We provide a detailed review of how solar power can be integrated into EV charging systems, looking at the technical, environmental, economic, and policy aspects [1][7][5]. By examining real-life case studies, we offer insights into how these systems can be effectively implemented [4][8].

It is crucial to have supportive policies and economic incentives to encourage the adoption of these technologies [1][9][10]. Our study aims to fill the gap in research about practical large-scale implementations [4][8]. We provide valuable insights for car manufacturers, utility companies, and policymakers to help transition to low-carbon transportation networks. Smart planning and innovation will be essential to tackle the current challenges, allowing us to create cleaner and smarter mobility solutions for future generations through solar energy integration [4][6][10].

Challenges facing the Indian EV industry



The primary challenge hindering the adoption of electric vehicles (EVs) in India is the lack of adequate charging infrastructure. While it is relatively straightforward to charge an electric scooter at home, charging an electric car presents more difficulties. Public charging options, such as dedicated EV stations or regular gas stations equipped with EV chargers, are preferred, but the availability of these facilities remains limited in many states [9][11]. Additionally, a significant portion of the batteries used in EVs sold in India are imported from countries like China and Korea, which raises overall costs [3]. Projections suggest that the demand for EV batteries in India could reach 65 GWh by the fiscal year 2030 [2].

In response to these challenges, the Indian government has implemented various initiatives aimed at promoting domestic production of EVs and their batteries. Two Production Linked

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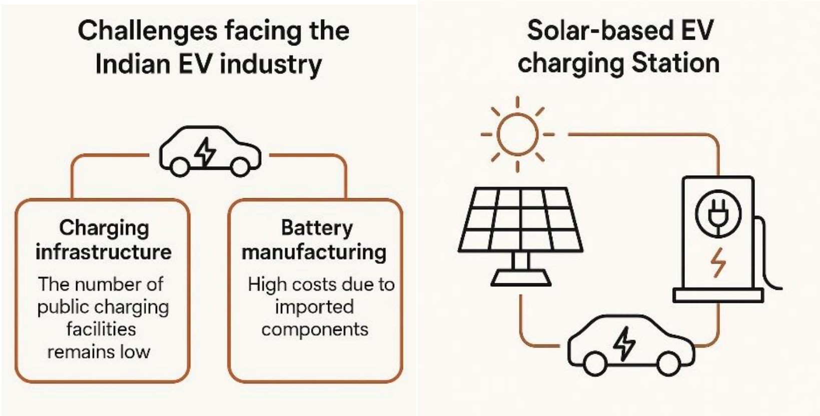
Incentive (PLI) schemes have been introduced to support the manufacturing of advanced automotive technologies, with budgets of approximately 260 billion and 180 billion rupees dedicated to battery production [10]. Alongside these major initiatives, the government has also enacted several smaller policies, such as reducing the Goods and Services Tax (GST) and waiving certain permits for EVs, to further stimulate sales and usage of electric vehicles [1][12].



Incorporating Solar Power into Electric Vehicle Infrastructure

The integration of solar energy and electric vehicle (EV) technology is a smart way to create a more sustainable transportation system [4][5][13][14]. This process uses solar panels to capture sunlight and convert it into electricity, which is then used to charge EVs. By doing this, we can reduce our reliance on fossil fuels, lower greenhouse gas emissions, and save on operational costs [4][5]. Thanks to advancements in solar and battery technology, this approach is becoming easier and more affordable to implement. There are two main types of solar EV chargers: Grid-tied and Off-grid [22][23][19][14].

1. Grid-Tied Solar EV Chargers:

Grid-tied systems connect solar panels to both the charging station and the regular electricity grid [4][7][5]. During sunny days, the solar panels generate electricity that can be used to charge EVs directly. If the solar panels produce more electricity than is needed for charging, the extra power goes back into the grid. This process is called net metering [4][15], which allows the owners of the charging stations to earn credits or payments for the surplus electricity they provide. At night or on cloudy days, when there isn't enough solar energy, the system automatically pulls electricity from the grid, ensuring that EVs can still be charged without interruption. Grid-tied systems work best in urban and suburban areas where the electricity grid is stable [9][16][24]. They offer flexibility and reliability without needing large batteries for storage.

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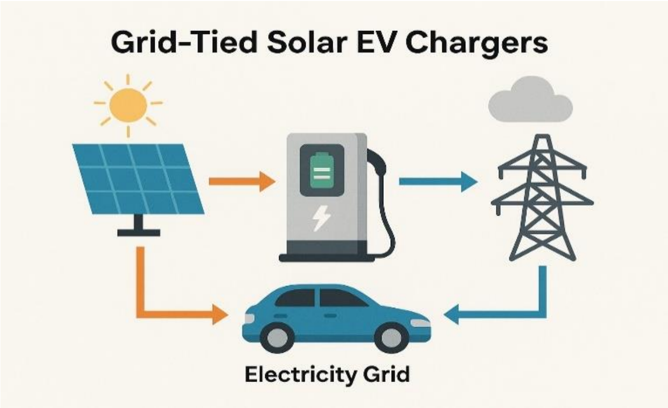
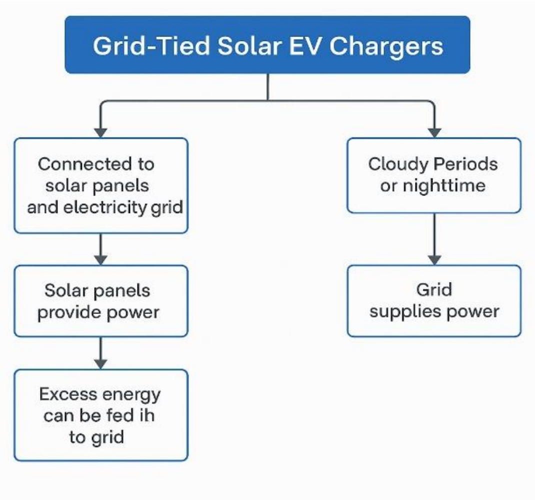


2. Off-Grid Solar EV Chargers:

Off-grid systems, on the other hand, do not rely on the electricity grid at all. They use only solar energy and usually come with battery storage to save extra electricity generated during sunny periods [4][5][14], which can be used when there isn't enough sunlight, such as at night or during cloudy weather. These chargers are particularly useful in remote or rural areas where the grid may not be accessible [8][11][17]. They provide energy access in places that lack reliable electricity. However, planning is crucial to ensure that the solar panels and batteries can meet the energy demand, especially during prolonged cloudy days.



While off-grid systems offer complete energy independence, they often require a higher initial investment due to the need for batteries and other backup components [4][18].

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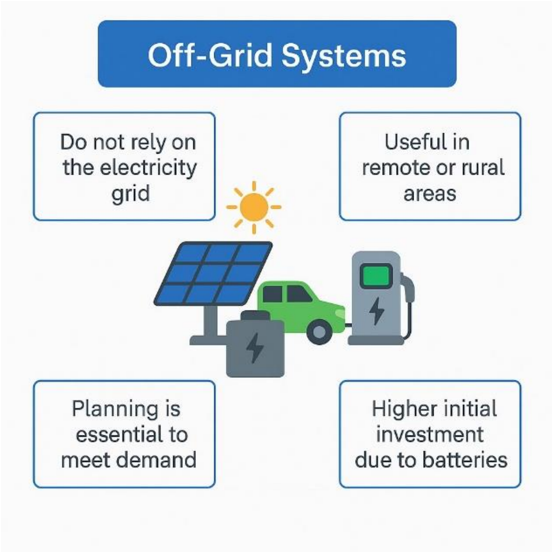
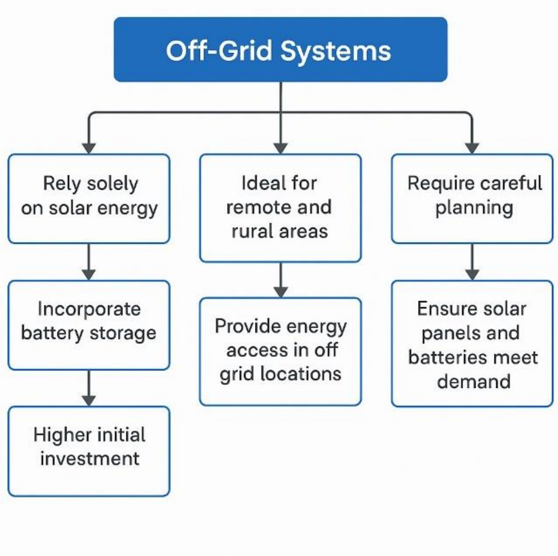


Both grid-tied and off-grid solar EV charging systems provide important environmental and economic advantages [4][7][13]. Grid-tied systems are better suited for areas with existing electricity infrastructure, offering cost savings and the ability to interact with the grid. Off-grid systems, while more expensive to set up initially, are essential for expanding EV charging options in regions with limited or no grid access [8][17]. As technology continues to improve, both types of systems will be important in developing a widespread network of renewable energy-powered EV chargers both in India and globally [19][2][16][18].



Solar-integrated EV charging systems merge solar photovoltaic (PV) technology with electric vehicle (EV) charging, providing a clean and renewable energy alternative [4][5][6]. By utilizing solar power instead of fossil fuels, these systems help decrease greenhouse gas emissions [4][13][14]. This integration fosters a transition towards sustainable transportation and encourages the use of renewable energy sources [4][3]. The inclusion of solar panels not only boosts energy efficiency but also delivers significant environmental advantages [4][14].

Received: August 05 ,2025

Additionally, these systems promote the broader adoption of solar PV technology [4][19]. From an economic perspective, they lower charging expenses by harnessing free solar energy, which enhances energy independence and strengthens grid reliability [4][7][16]. In summary, these systems contribute to reducing reliance on fossil fuels while supporting overall energy security [6][10][12][20].

Financial Considerations and Advantages of Solar-Powered EV Charging Stations

Solar-powered EV charging stations offer significant long-term financial and environmental advantages, particularly when evaluated across several important areas.

1. Cost Comparison Between Solar Energy and Grid Electricity

A cost analysis of solar energy versus grid electricity reveals significant differences in long-term affordability and price stability. The costs of solar power have dropped substantially over the last ten years, thanks to improvements in photovoltaic technology, increased production efficiency, and supportive policies. Once solar PV systems are installed, they incur minimal operating expenses, and the levelized [4][13] [36][37].cost of electricity (LCOE) remains consistent for decades, as sunlight is free and not subject to market price variations. In contrast, the costs of grid electricity are affected by fuel prices, the energy generation mix, and regulatory policies, which frequently result in periodic increases in tariffs. Furthermore, in many areas, grid electricity is still partially or entirely sourced from fossil fuels, making it more vulnerable to geopolitical issues and supply chain challenges. Throughout the lifespan of the system, solar power generally offers a lower and more predictable cost per kilowatt-hour compared to traditional grid electricity [7][14][21].

2. Savings for Customers

Savings for customers using solar-powered EV charging stations arise from three key factors. **Reduced charging costs** are achieved because solar-generated electricity is generally cheaper than grid electricity over the long term, especially after the initial infrastructure investment is recovered. This cost advantage becomes more pronounced as grid tariffs rise, allowing EV owners to enjoy consistent savings per kilometer driven [7][16] [36][37]. **Stability and predictability** in energy expenses come from the fact that solar power is not subject to the same market fluctuations as fossil fuels or variable grid tariffs, giving customers a more reliable basis for budgeting their transportation costs4][2]. In some cases, operators or municipalities may offer **free charging options**—often supported by subsidies, advertising partnerships, or surplus solar generation—which can further lower or even eliminate charging expenses for users, enhancing the economic appeal of EV ownership [1][17].

3. Impact on Overall EV Ownership Costs

The influence of solar-powered EV charging on the overall costs of electric vehicle ownership is significant, mainly through savings on fuel and maintenance, which promote greater EV adoption. By using solar energy instead of grid electricity or conventional gasoline, owners can enjoy considerably lower "fuel" costs, particularly once the solar infrastructure has been established and is operational[7][13][16]. Unlike gasoline prices, which can fluctuate due to

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market conditions, solar energy offers a stable and predictable pricing model over time. Additionally, electric vehicles require less maintenance compared to internal combustion engine vehicles, as they have fewer moving parts, do not require oil changes, and experience less wear on components like brakes—benefits that are further enhanced when powered by renewable energy systems with low operational costs. [6][14].These financial benefits effectively lower the total cost of ownership, making EVs more competitive and attractive to consumers. As operating expenses decrease, the affordability gap between EVs and traditional vehicles diminishes, leading to increased adoption rates and supporting a broader shift towards sustainable transportation [1][17].

4. Reduction of Greenhouse Gas Emissions and Fossil Fuel Dependence

Solar-powered EV charging stations are essential for decreasing greenhouse gas emissions and reducing reliance on fossil fuels by offering a clean and sustainable alternative to traditional charging methods. [4][5][13]. These systems produce zero tailpipe emissions at the point of use, ensuring that electric vehicles charged directly from solar energy do not contribute to local air pollution or greenhouse gas emissions. [2][10]. While the manufacturing of photovoltaic panels and EV batteries does involve some emissions, these are largely offset over time as the systems generate renewable electricity and reduce the need for fossil-fuel-based energy, leading to significantly lower lifecycle emissions. Moreover, incorporating solar energy into EV charging diversifies the energy supply, lessening dependence on centralized fossil-fuel power plants and improving energy resilience against market volatility [13][14].On a larger scale, the widespread adoption of solar EV charging can significantly aid national and global efforts to reduce emissions. By diminishing the demand for petroleum-based fuels, these systems also mitigate the environmental impacts associated with fossil fuel extraction, processing, and transportation. Additionally, locally produced solar energy fosters energy independence by decreasing reliance on imported oil and gas, thereby enhancing national security and promoting long-term economic sustainability [2][4] [20]

Constraints in Establishing Solar-Integrated EV Charging Points

The table 1 organizes the obstacles associated with the development of solar-integrated EV charging stations into four main categories: technical, economic, regulatory, and operational constraints, providing a clear and research-focused summary.

Technical challenges arise from the intermittent nature of solar energy, the need for substantial space, and the absence of standardized interoperability.

Economic difficulties are linked to significant initial investments, extended payback durations, and a lack of financial support options.

Regulatory challenges encompass inconsistent policies, complicated approval processes, and varied infrastructure standards.

From an operational perspective, these initiatives confront issues such as a shortage of skilled labor, limitations in urban space, and fluctuations in performance due to weather conditions and seasonal variations.

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Category	Key Constraints	References
Technical Limitations	• The variability of solar energy results in inconsistent charging availability. • Significant land or rooftop space is needed for solar panel installations. • Challenges related to grid integration, particularly in managing bidirectional energy flow. • Battery life can be adversely affected by inconsistent charging rates caused by changing solar output. • There is a lack of standardized technology for seamless solar-EV charging compatibility.	[4], [5], [6], [7], [14], [17], [37], [39], [42]
Financial Challenges	• Substantial upfront investments are required for solar PV systems, inverters, and energy storage solutions. • Extended payback periods are common, particularly in areas with low usage rates. • Limited funding options and hesitance from investors due to market uncertainties. • The costs associated with hybrid systems that include energy storage are higher compared to traditional grid-based charging.	[1], [7], [12], [16], [18], [20], [28], [41]
Regulatory Challenges	• Fluctuating government policies and a lack of long-term incentives create uncertainty. • Complicated approval procedures for connecting solar PV systems to the grid. • Absence of consistent standards for solar EV charging infrastructure. • Electricity pricing structures that hinder the integration of renewable energy sources.	[9], [10], [11], [19], [21], [24], [40], [43]
Operational Challenges	• There is a shortage of skilled workers for the installation and maintenance of systems. • Urban environments often face space limitations for implementing solar PV systems. • Predicting energy demand and solar generation trends can be challenging. • Performance can vary significantly based on seasonal changes and weather conditions.	[3], [8], [13], [15], [22], [25], [36], [38]

Table 1. Constraints in Establishing Solar-Integrated EV Charging Points

Financial Considerations for Solar Infrastructure: Capital Demands, Funding Strategies, ROI, and Economic Feasibility

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Projects involving solar infrastructure, especially those linked to electric vehicle (EV) charging networks, typically require substantial initial capital investment due to expenses associated with photovoltaic panels, battery storage systems, power electronics, and site development. To secure the necessary funding, a variety of financial strategies must be employed, including equity investments, bank financing, government grants, and collaborations between public and private sectors. The financial appeal of these projects largely hinges on their return on investment (ROI), which is shaped by factors such as energy production, savings on operational costs, and available incentives. Moreover, a thorough evaluation of economic viability should examine payback durations, total lifecycle costs, and potential income from additional services such as grid support or energy trading.

Table: Economic Considerations for Solar-Integrated EV Charging Infrastructure

Aspect	Detailed Explanation	References
Capital Demands	Significant initial expenditure is required for procuring solar PV panels, inverters, battery storage units, mounting structures, and control systems, as well as for installation, commissioning, and integration with the local grid.	[16][18]
Funding Strategies	Potential financing approaches include equity investments, commercial or concessional loans, government subsidies or incentives, and public–private partnerships that share investment risks and operational responsibilities.	[12][18]
Return on Investment (ROI)	ROI is determined by multiple factors such as total annual energy generation, electricity tariff rates, operational savings from reduced grid dependency, and the extent of system utilization over its lifespan.	[7][16][41]
Economic Feasibility	A comprehensive assessment covering payback periods, total lifecycle costs (including maintenance and replacements), and projected profitability is essential to justify project viability and attract investor confidence.	[1]

Non-Standardized Charging Connectors and Infrastructure

The lack of consistent standards for charging connectors and associated infrastructure presents significant technical and logistical hurdles in expanding electric vehicle (EV) charging networks, particularly those utilizing solar energy. Currently, various EV manufacturers utilize different types of connectors, charging protocols, and power ratings—such as CCS (Combined Charging System), CHAdeMO, GB/T, and Type 2—each having distinct specifications for voltage, current, and communication methods. This variability creates compatibility

Received: August 05 ,2025

challenges, necessitating either multiple charging ports or expensive adapter systems at charging stations [3][9].

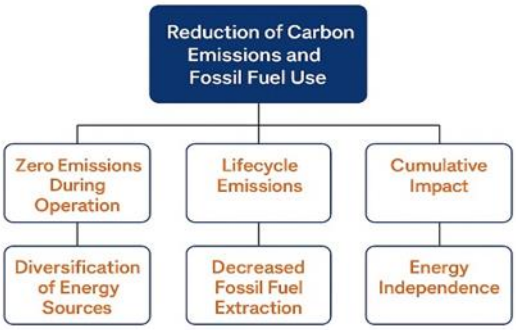
From the infrastructure standpoint, variations in electrical setups, grid integration needs, and safety standards further hinder interoperability. This issue is particularly acute for solar-powered EV charging stations, where compatibility among power electronics, storage systems, and control interfaces is essential for seamless operation with both the solar PV system and the EV charging equipment. The absence of a standardized framework leads to higher installation costs, extended project timelines, and decreased convenience for users [25][26][42].

Additionally, this fragmentation complicates large-scale planning and policy development, as both governments and private entities must navigate multiple technical configurations when creating charging corridors or incentive programs [27][28]. Establishing a unified standard could significantly improve efficiency, lower costs, and bolster consumer confidence, facilitating quicker adoption of both electric vehicles and solar-powered charging networks [2][29][30].

Impact of Solar PV in Electrical Vehicle Infrastructure

The incorporation of solar photovoltaic (PV) technology into electric vehicle (EV) infrastructure is significantly enhancing the sustainability and energy efficiency of contemporary transportation systems. Solar PV serves as a clean and renewable energy source, allowing EV charging stations to function with reduced reliance on fossil fuels, thereby lowering greenhouse gas emissions. By utilizing solar energy, these stations help decentralize power generation, alleviating pressure on the national grid, particularly during peak demand periods [15][43].Furthermore, solar-powered EV charging infrastructure can lead to long-term cost savings by lowering electricity expenses and protecting operators from variable grid electricity prices. In rural or remote areas where grid access may be limited or unreliable, solar PV systems provide an effective standalone solution, improving energy availability and encouraging EV adoption. Additionally, pairing solar PV with energy storage solutions like batteries ensures that charging remains accessible even during times of low sunlight. Overall, the role of solar PV in EV infrastructure is significant, facilitating the shift toward cleaner transportation, enhancing energy security, and contributing to national renewable energy objectives [25][35].

Received: August 05 ,2025



Aspect	Positive Impacts	Negative Impacts / Challenges
Environmental Impact	• No emissions during operation • Aids in achieving decarbonization goals	• Energy generation is intermittent • Output is affected by weather conditions
Operating Costs	• Very low costs after installation • Decreases dependence on grid and fossil fuels	• High initial installation costs • Relies on government incentives for viability
Grid Load Management	• Decreases peak demand on the grid • Enhances demand-side energy management	• Can destabilize the grid if not properly managed • Requires advanced synchronization techniques
Energy Independence	• Reduces reliance on fossil fuels • Promotes local and resilient power sources	• Requires storage systems for autonomy • Performance limited by weather and available sunlight
Return on Investment (ROI)	• Provides long-term savings • Attracts investors focused on sustainability	• Extended payback periods • ROI is sensitive to location and usage patterns
Off-grid Capability	• Facilitates charging in remote locations • Suitable for rural electrification	• Limited space for solar panels in urban areas
Space Requirements	• Can be installed on rooftops or parking structures	• Requires a significant surface area

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		• May not be practical in densely populated areas
Energy Storage	• Allows for charging during the night and on cloudy days with battery systems	• High costs associated with batteries • Concerns regarding disposal and lifecycle management of battery technology
System Maintenance	• Low ongoing operational costs	• Necessitates regular cleaning and maintenance • Efficiency may degrade over time (approximately 0.5–1% annually)

Future Scope

The intelligent integration of solar PV technology into EV charging networks presents significant opportunities for promoting sustainable urban mobility. Future research should aim to improve the efficiency and affordability of battery storage to ensure continuous solar-powered charging [4][14].The development of AI-driven energy management systems could enhance solar generation, load balancing, and grid interaction [8][13].

In India, implementing policy reforms and incentives will be essential to address challenges related to high installation costs and land use [1][11][12]. Innovations such as modular, mobile, or rooftop PV-based chargers can effectively serve space-limited urban environments [8][15]. Additionally, advanced forecasting models can help manage intermittency and support stable grid integration [30][31].

Economic assessments that evaluate lifecycle costs and return on investment will be vital for guiding large-scale implementations [14][18]. Public-private partnerships can expedite infrastructure development, particularly in rural and semi-urban areas [10][12]. Furthermore, environmental impact assessments should encompass comprehensive strategies for managing solar panel and battery disposal at the end of their life cycles [13][14].

Overall, integrated solar EV systems have the potential to create a cleaner, more cost-effective, and energy-resilient transportation future for India and beyond [31][32].

Conclusion

Integrating solar PV technology into EV charging networks presents a sustainable and cost-efficient approach to meeting the increasing energy needs associated with electric mobility [4][17]. This integration substantially decreases carbon emissions, enhances energy independence, and reduces the overall cost of owning electric vehicles [13][14]. While

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challenges such as high initial investments, space limitations, and energy storage concerns exist, the long-term environmental and financial advantages are considerable [3][5].

In India, it is crucial to tackle issues related to grid capacity, infrastructure gaps, and the need for supportive policies to facilitate widespread adoption [1][3][26]. Utilizing advanced technologies for smart integration can improve system efficiency, reliability, and scalability [2][13]. Additionally, solar-powered EV charging systems are in line with India's renewable energy objectives and urban sustainability initiatives [4][10]. Collaborations between the public and private sectors, along with innovative financing strategies, will be vital in addressing economic obstacles [12][18].

As the electric vehicle market continues to grow, the integration of solar energy will be essential in creating a clean transportation landscape [33][34]. Ongoing research, regulatory backing, and technological advancements will propel this shift forward [1][21]. Ultimately, developing solar-powered EV infrastructure signifies a significant move toward a more sustainable and resilient future [4][14].

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