Challenges and opportunities in integrating electric vehicles with distributed renewable generation

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ABSTRACT

Electric vehicles (EVs) and distributed generation (DG) based on renewable energy sources (RES), mainly solar photovoltaics (PV) and wind, are the two main pillars of the current smart grid. EVs are growing in popularity. They promise improved resilience and sustainability through their synergistic combination. This review essay offers a thorough analysis of the opportunities and difficulties present in this pairing. We examine that managing the dual intermittency of renewable energy and EV mobility puts pressure on grid stability and power quality. This study carefully compares the performance, economic feasibility, and grid implications of several integration architectures, ranging from hybrid systems and vehicle-to-grid (V2G) ecosystems to solar and wind-powered charging stations. This work also analyzes the important trade-offs between grid hosting capacity (HC), cost vs reliability, and infrastructure centralization. According to the study, the main socioeconomic and technical obstacles to scalability are antiquated regulations, battery degradation issues, and a lack of standardized interoperability. To turn EVs from a grid burden into a versatile asset for a decarbonized energy future, the study concludes by outlining critical future research topics, highlighting the necessity of AI-driven energy management systems (EMSs), sophisticated vehicle-to-everything (V2X) services, and dynamic HC analysis.

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1. INTRODUCTION

Massive efforts have been made in the past ten years to promote renewable energy, climate consciousness, and environmental sustainability. There is now more demand for green energy and environmental reductions. Authorities throughout the world are enacting a wide range of policies and doing research to lower carbon emissions and support green energy [1]. The automotive industry is a significant source of greenhouse gas (GHG) emissions. One significant step that would assist authorities in achieving their objective would be decarbonizing the transportation industry [2], [3]. According to research, the demand for oil connected to transportation will rise by 54% by 2035. The next 20 years will see a sharp rise in oil costs, according to the energy information administration (EIA) [4]. This has led to the emergence of several efforts to reduce oil consumption. Electric vehicles (EVs) are a practical option for the transportation sector, and their growth is remarkable. Future internal combustion (IC) EVs are anticipated to be driven out in favour of EVs, according to an economic study. The electrical grid could benefit from a distributed, decentralized power source from EVs [5].

When the grid needs aid, EV technology can be of assistance. The past few years have also seen a greater integration of massive renewable energy-based distributed generation (REDG) supplies like wind and photovoltaic (PV) solar energy into the grid. These REDG are widespread and challenging to predict. To address stringent energy regulations and energy safety issues, REDG's market share in the electrical sector has grown significantly in the past decade [6]. The ability to charge and discharge the battery cells gives EVs several advantages, but they also present several challenges to the electrical infrastructure. These issues necessitate changes to the electric grid's strategic oversight and regulation [7]. Both a potential standby source of electricity for the electrical grid and a source of erratic, hard-to-predict dynamic loads are associated with electric automobiles. EVs are sometimes perceived by individuals as being more costly for upkeep than traditional gas-powered automobiles [8].

The 20th century marked the beginning of EV exploration. The investigation first concentrated on parts like machinery, driving structures, batteries, and fuel cells [9]. Considering EVs as a component of the user load and examining them from the standpoint of handling loads became crucial as their adoption accelerated. With the advent of smart grid technologies in the electricity industry, the research took a different turn [10]. The EV business has undergone a revolution due to the creation and adoption of renewable energy sources (RES) in utilities and the growth of a smart grid. EVs are not only dependable energy sources but also effective mobility aids, according to numerous studies. They maintain the utility grid by offering a range of services. These provide important capabilities that are collectively referred to as vehicle-to-everything (V2X) services. The current energy and power sectors are mostly focused on the vehicle-to-grid (V2G), vehicle-to-home (V2H), and vehicle-to-vehicle (V2V) [11], [12]. Plug-in EVs (PEVs) and EVs are the main focus of the current vehicle industry. Nevertheless, despite all of the advantages, some obstacles prevent EV innovation from being widely adopted. Range anxiety, poor charging facilities, expense of ownership, and insufficient customer knowledge are the main issues impeding the widespread use of EVs [13], [14]. Understanding the change in interest in the energy and automotive markets is crucial in this regard.

This review provides a critical synthesis of the integration of EVs with renewable-based DG. It contributes a structured analysis of integration architectures, evaluating their trade-offs in cost, reliability, and grid impact. The study delineates the interconnected technical, economic, and regulatory challenges hindering adoption, particularly focusing on managing double intermittency, battery degradation from V2G services, and outdated policies. Furthermore, it outlines a forward-looking roadmap prioritizing AI-driven energy management, standardized interoperability, and dynamic grid support mechanisms to transform EVs from a grid burden into an essential asset for a resilient, decarbonized energy system. The organization of work is as follows: section 2 covers the overview of EV and integration of EVS with RES-based DGs. Section 3 discusses the results and analysis including the comparison of architecture-based approaches, various aspects of challenges, trade-offs, and future research directions of the EVs with DGs. Lastly, the conclusion of the overall work is in section 4.

2. METHOD

2.1. Electric vehicle technology

Dependency on fossil fuels is the main issue with internal combustion engine (ICE) automobiles, which raises worries about energy independence and carbon dioxide (CO_2) emissions. EVs reduce the demand for crude oil-fueled transport and reduce GHG emissions as a result of the strain on fossil fuels and the increase in emissions of CO_2. The four main types of EV technologies are typically battery EV (BEV), fuel cell electric vehicle (FCEV), hybrid electric vehicle (HEV), and plug-in hybrid electric vehicle (PHEV) [15]. The degree of electrification rises from left towards right. Gasoline and diesel fuel are two of the main sources of CO_2 emissions from typical vehicles. Because of this, hybrid vehicles emit less CO_2 than vehicles with ICEs. Zero-emission vehicles that use hydrogen fuel cells or batteries fall into the PEEV and BEV types, accordingly [16].

a. BEV and FCEV: the battery package is the only electrical source in a complete EV. In other words, EVs contribute to the fight against climate change by lowering GHG emissions more effectively than HEVs. The kinetic energy (KE) produced as the automobile slows down is transformed back into electrical power by the EV's regenerative braking system, which can be retained by the battery. Because EVs stop and start frequently, they are consequently better for driving in towns because they can recover some of the KE they use [17]. An FCEV is similar to an EV that has an electric powertrain. However, rather than using power, it uses hydrogen that can be preserved in an FC container. This vehicle doesn't emit any pollutants because it does not generate exhaust gases. The two different powertrain combinations that are possible for FCEVs are referred to as FCEVs and FC HEVs. Applications like public transportation, cranes, and subways, that need steady power at moderate speeds are where the FCEV excels. By employing a variety of energy optimization techniques, FCEV manufacturers such as Hyundai, Toyota, and Honda create vehicles that are superior in terms of fuel consumption and vehicle effectiveness [18].

b. HEV and PHEV: a battery pack or an ICE may power a HEV. Due to its ability to run on both electricity and gasoline, the HEV is a dual-power provider vehicle. Because they can recharge their battery packs while braking, HEVs are better for driving in cities. The vehicle must be started and stopped frequently when driving in a metropolis. For this reason, HEVs are the best vehicles to drive in cities. For the time being, for the next ten years, HEVs appear to be the most economical option because fully EVs continue to be in their existence. The HEV's ICE engine and electrical motor are tuned to minimize emissions and energy waste. HEVs are now more financially and ecologically feasible due to their greatly enhanced efficiency and fuel economy. The battery's expensive buying cost is a drawback [19]. An electric motor driven by a pack of batteries and an ICE fuelled by a separate fuel, like gasoline or diesel, is known as a PHEV. The battery packages of PHEVs are frequently larger than those of traditional HEVs. For shorter journeys, a vehicle can run primarily on electricity if its battery pack is bigger. PHEVs can operate on liquid gasoline contained in their tanks, which eliminates the need to empty their batteries during travel over long distances. Whenever the amount of fuel to consume is determined by the vehicle's on-board software based on its operating mode [20].

Table 1 shows an exhaustive comparison of each EV type, including its benefits and drawbacks. All things considered, every kind of EV innovation has benefits and drawbacks, and users must choose the one that best meets their requirements. The ideal EV for a particular circumstance will ultimately rely on the customer's routine, objectives, and financial circumstances [21].

Table 1. Comparative summary of EV types

EV type	Description	Advantages	Limitations
BEV	- Vehicles that run entirely on batteries with rechargeable cells - No ICE, powered by the grid	- Excellent energy economy - Minimal operating and repair expenses - Perfect for short-distance and urban travel - No tailpipe emissions	- A short driving distance, longer charging times - Expensive replacement of batteries - In certain places, charging facilities may be lacking
FCEV	- Utilizes onboard hydrogen fuel cells to produce electricity - Merely releases water vapour	- Greater driving range than BEVs - Quick recharging (similar to ICE vehicles) - Quiet operation - No emissions from the tailpipe	- The expensive nature of fuel cell systems - The lack of facilities for hydrogen refuelling - The potential energy intensity of hydrogen production
HEV	- Incorporates a small electric motor, batteries, and an ICE - Regenerative braking or the engine, rather than a plug, is used to charge the battery	- Higher fuel economy compared to traditional cars - Emissions are lower than with pure ICE - No additional equipment is required for charging - They are widely accessible and reasonably priced	- The lower energy efficiency of BEVs - Its intricate mechanical form - Fewer ecological advantages than BEVs - Inability to run on electricity alone for extended periods
PHEV	- Like HEVs, but with bigger, independently chargeable batteries - Able to operate for short distances using only electricity	- Capable of running on electricity for brief excursions - The adaptability of ICE for extended journeys - Fuel expenses and pollutants are reduced - Switching from ICE to EV is simpler	- It costs more than HEVs - Its electric-only range is only 15 to 50 miles - It needs to be charged for maximum performance - Even with ICE, GHGs are still released

2.2. Electric vehicles integration with renewable energy sources-based distributed generations

There is reason to be optimistic about the progress made in integrating RES-based DG into the electrical grid. When RES, such as solar PV and Wind, are unpredictable and variable, the electrical system faces challenges. Numerous studies [22]-[24] have demonstrated that solar PV systems and wind energy conversion systems (WECS) can be securely and economically connected to the grid. To ensure that the grid can handle the power generation of these RE-based DG, regulated transit loads or fixed battery storage systems (BSS) might be introduced. Figure 1 illustrates that solar PV and wind energy can work together. By integrating EVs and wind energy, variability in power from these RE-based DG can be reduced in the V2G mode through installing a CS in an open environment or business. Also, believe that the control and transmission techniques needed for the charging and V2G situations are present in this structure.

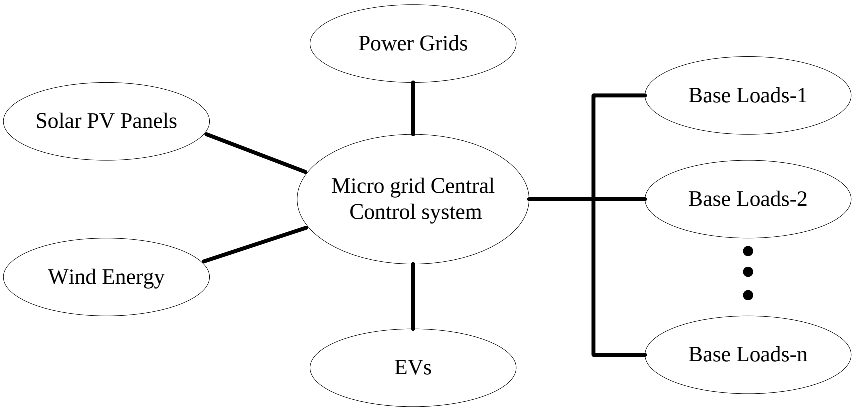

Figure 1. Solar-PVs and wind energy connecting EVs to the grid

2.2.1. Technical aspects

Integration of EVs with DG has been explored across solar, wind, and hybrid configurations, focusing on optimized charging, resource management, and grid support. For solar-based integration, Vermeer *et al.* [25] proposed a two-stage intelligent charging system combining PV forecasting and Li-ion battery degradation modelling, reducing energy costs by up to 98.6% compared with unregulated charging. Robisson *et al.* [26] demonstrated real-world solar EV charging infrastructure (EVCI) at Cadarache, showing up to 60% increase in self-consumption ratio while meeting user needs. Adeagbo *et al.* [27] applied particle swarm optimization (PSO) for optimal PV DG placement in radial distribution networks, validating reduced losses and improved bus voltage profiles on the IEEE 33-bus system. Manzolini *et al.* [28] highlighted the importance of PV and EV forecasting accuracy, showing that combined prediction precision significantly impacts operating costs. Bonela *et al.* [29] extended the concept by integrating solar DG with distribution static synchronous compensator (DSTATCOM) for an EV charging ecosystem, using enhanced PSO for techno-economic optimization across 33- and 108-bus distribution networks.

In wind-based integration, Noman *et al.* [30] examined powering EV charging stations (EVCSs) directly from wind energy, proposing an interval-based method aligned with EVCS time windows. Shang *et al.* [31] emphasized V2G scheduling with wind power, showing reduced peak-to-valley variation and improved grid economics while ensuring wind power utilization. Rehman *et al.* [32] introduced a beluga whale optimization algorithm for sizing wind turbine generating systems (WTGSs), achieving improved convergence and reduced network losses. Ananwattanaporn *et al.* [33] analyzed various wind DG placements in a 22 kV distribution network, confirming voltage-drop mitigation under different fault scenarios.

For hybrid solar–wind approaches, Angamarca-Avendaño *et al.* [34] tested a hybrid PV–wind powered EV (Chok S2) with a charge equalizer, achieving 20% efficiency gains and significant renewable contribution during operation. Zenhom *et al.* [35] proposed a hierarchical bi-level hosting capacity optimization framework combining dynamic tariff–based demand response and smart inverter Volt/VAR control, achieving significant improvements in DG and EV hosting capacity in an IEEE 33-bus system. Zhu *et al.* [36] proposed a path-demand-based optimization framework for interstate EVCSs, determining the location and capacity of hybrid wind–solar storage charging stations to meet diverse EV charging demands. Finally, Kim *et al.* [37] developed a realistic EV penetration modeling approach for low-voltage distribution networks and microgrids using practical cable, load, and vehicle access data.

2.2.2. Environmental aspects

Singh *et al.* [38] analyzed solar-powered EVCSs for six Indian cities, showing that monocrystalline PV units improve energy efficiency and reduce CO_2 emissions. Shafiq *et al.* [39] studied solar PV-based EVCS for security bikes in Azad Jammu and Kashmir, highlighting the eco-friendly and economic viability of renewable-powered charging. Rotas *et al.* [40] assessed EV–PV synergies in Berlin and Los Angeles using Modelica models, finding daily solar driving contributions of 20.3% and 30.4%, respectively. Osman *et al.* [41] validated an integrated PV–BSS–EV system with smart energy management, achieving 92.2% solar utilization and a yearly CO_2 reduction of 6239 kg.

2.2.3. Financial aspects

Abbaspour *et al.* [42] performed a techno-economic assessment of hybrid renewable energy systems across multiple climate zones, highlighting the trade-off between renewable penetration and carbon emissions. Sagaria *et al.* [43] investigated photovoltaic-integrated electric vehicles under real-world conditions, demonstrating substantial improvements in driving range and reduced charging frequency. Manousakis *et al.* [44] reviewed EV–RES integration, stressing the financial impacts of EVCS deployment and storage systems. He and Fathabadi [45] proposed a standalone PV-based EV charging station with fuel cell integration, demonstrating improved lifetime cost-effectiveness compared to conventional battery-based systems. They showed that a power-following control strategy reduced the required battery capacity by approximately ~20x. Hossain *et al.* [46] examined electric vehicles from a sustainable development perspective by integrating technological, environmental, and policy dimensions, providing a holistic assessment of global EV viability and offering insights valuable for both researchers and policymakers. Vankina *et al.* [47] optimized a hybrid thermal–wind–EV plant for higher profitability and frequency stability in deregulated grids. Shojaabadi *et al.* [48] introduced a game-theoretic framework to model competition among EV aggregators, enhancing wind power producer participation in day-ahead electricity markets.

2.2.4. Socio-cultural aspects

Dagteke and Unal [49] proposed an EVCS using PV and fuel cells for tourist regions, showing that such infrastructure can support households, EV charging, and hydrogen production while preserving cultural heritage. Moreno-Pacheco *et al.* [50] investigated wind energy recovery from vehicular motion, concluding that residual airflows could power ~4500 homes, demonstrating a socio-technical opportunity to turn waste energy into usable electricity. The other approaches [51]-[54] are evaluated to realize the impact of EVs on DGs.

3. RESULTS AND DISCUSSION

The technical performance, environmental advantages, financial viability, and sociocultural significance are all tied together in this debate to demonstrate the way the EV–DG integration promotes grid stability, cost and emission savings, and social acceptance as well. The performance analysis of recent works based on technical, environmental, financial and social aspects for EV with RES-based DG is tabulated in Table 2. By integrating renewable energy, the technical results of the evaluated research show significant gains in EV charging performance. The cost of smart charging using PV and Li-ion batteries was reduced by 98.6% [25], and experimental PV-EV charging systems used 174 kWh of solar energy to meet a daily need of 214 kWh [26]. Multi-bus systems claimed loss reductions of 36–40%, while DG integration into distribution networks decreased active and reactive power losses by over 50% [27]. EVCSs driven by wind generated 20–35 kWh per day at wind speeds of 3.5–6.2 m/s [30]. V2G-based scheduling reduced curtailment by 12–18%, increasing wind utilization to 92.7% [32]. It also shown excellent grid-supporting potential with charging efficiencies of up to 92% [34], voltage drop decreases of 6–12%, and hosting enhanced capacity of 15–20% [37]. Environmental findings from non-technical viewpoints demonstrate that EV-renewable systems dramatically lower energy consumption and emissions. In India, 414 EVs saved 7950 kg of CO_2 a year when they were charged [38], and hybrid PV–battery–EMS systems reduced CO_2 by 6239 kg and achieved 92.2% solar autonomy [41]. According to financial studies, blockchain platforms reduced energy trading costs by 25% [43], hybrid designs saw 75–85% RE penetration [42], while deregulated systems saw cost savings of 11–12.6% [47]. With rooftop PV meeting 60–80% of EV demand, smart houses saw bill savings of 30–45% [46]. Socio-culturally, mobile wind harvesting from automobiles achieved 85% efficiency at 19.5 m/s wind speeds, while charging stations in historic areas offered round-the-clock, continuous service with 65% solar contribution [49], [50].

Combining renewable energy with EV charging improves grid efficiency and sustainability. Technically, advancements in charging efficiency, voltage stability, and loss reduction suggest that EVCS can become active grid-support units by integrating PV, wind, and V2G technologies, therefore decreasing reliance on traditional power. The stated results, which include a 92% charging efficiency [31] and a 50% loss reduction, attest to the technical maturity of hybrid solutions. While demand-side flexibility is made possible by V2G, which guarantees better use of renewables, wind and solar complementarities further reduce variability. The results support the dual function of EVCS in cost optimization and decarbonization from an environmental and economic standpoint. The viability of renewables-driven EV infrastructure is demonstrated by significant cost savings (up to 45% in households) and CO_2 reductions (up to 7950 kg yearly) [38]. Furthermore, deregulated hybrid markets and blockchain-based trade show new financial avenues for deployment scaling. With constant service availability in tourist areas and creative mobility-based wind harvesting demonstrating adaptability across a range of settings, sociocultural implications underscore the need for accessibility. When taken as a whole, these results demonstrate that EVCS solutions with renewable integration offer a comprehensive route to a sustainable, economical, and socially inclusive energy transition.

Table 2. Performance analysis of recent works based on various aspects for EV with RES-based DG

References	Area of study	Results
	Technical aspects	
Vermeer *et al.* 2020 [25]	Smart charging (PV+Li-ion)	Energy cost ↓ 98.6% vs uncontrolled.
Robisson *et al.* 2022 [26]	Experimental PV–EV	19 charges (during sunny days); 214 kWh used; 174 kWh PV generated.
Adeagbo *et al.* 2022 [27]	Solar DG in distribution	Power losses ↓ 49.7% (active), ↓49.4% (reactive).
Manzolini *et al.* 2024 [28]	PV–EV microgrids	operating costs ↓15%; grid stability ↑10%.
Bonela *et al.* 2025 [29]	Solar DG+EV (distribution)	Power losses ↓36% (33-bus), ↓40% (108-bus).
Noman *et al.* 2020 [30]	Wind-powered EVCS	Avg. wind availability: 3.5–6.2 m/s; supply 20–35 kWh/day.
Shang *et al.* 2023 [31]	V2G+wind	V2G cut wind curtailment ↓12–18%; wind use efficiency ↑92.7%.
Rehman *et al.* 2023 [32]	Wind+EV loads	Voltage drop ↓10–12%; losses ↓8%.
Ananwattanaporn *et al.* 2024 [33]	Wind DG in 22 kV	Voltage drop ↓6–8%.
Angamarca-Avendaño *et al.* 2024 [34]	PV+wind EV with equalizer	Vehicle efficiency ↑20%; energy balance ↑15%; charging ↑92%.
Zenhom *et al.* 2025 [35]	EV and DG hosting capacity enhancement using DR and smart inverter Volt/VAR control	DG-HC increased by >133%; combined DG–EV HC improved by ~49.2% (DG) and ~61.2% (EV) in IEEE 33-bus system.
Zhu *et al.* 2025 [36]	Off-grid wind–solar EVCS	RE use ↑20%; 90% self-consistency.
Kim *et al.* 2021 [37]	EV penetration modeling in low-voltage microgrids	Developed a realistic EV penetration model using practical cable, load, and vehicle access data.
	Environmental aspects	
Singh *et al.* 2021 [38]	Urban India (EVCS)	414 EVs charged/yr; CO_2 reduced ~7950 kg.
Shafiq *et al.* 2022 [39]	EV charging for security bikes	Storage cost USD 0.191; backup 3.14 hrs; 45% battery backup.
Rotas *et al.* 2024 [40]	Urban environments	Annual energy and GHG cut 44–59%; charging cost savings.
Osman *et al.* 2025 [41]	PV+battery+EV+EMS	92.2% solar autonomy; 6239 kg CO_2 reduction.
	Financial aspects	
Abbaspour *et al.* 2023 [42]	Techno-economic analysis of hybrid renewable energy systems	Identified climate-dependent trade-offs; A Coruña achieved 95.5% renewable share with lowest emissions.
Sagaria *et al.* 2022 [43]	PV-integrated EVs	Driving range improved by 30–50% (Microcar) and 30–100% (5-seater) with reduced charging frequency.
Manousakis *et al.* 2023 [44]	RE+EV integration review	Capital costs $500–800/kW; financing gap ~30%.
He and Fathabadi 2020 [45]	Solar–fuel-cell-based standalone EV charging station	Fuel cell system reduced lifetime cost compared to battery banks while ensuring permanent operation.
Hossain *et al.* 2022 [46]	EVs and sustainable development	An integrated technology–environment–policy framework assessing global EV viability
Vankina *et al.* 2024 [47]	Hybrid thermal–wind–EV	Cost reduction 11–12.6%; RE penetration ↑20%.
Shojaabadi *et al.* 2022 [48]	EV aggregators and wind power participation in electricity markets	Game-theoretic EVA competition enhanced wind power producer participation in day-ahead markets.
	Socio-cultural aspects	
Dagteke and Unal 2024 [49]	Tourist/historic regions	24/7 charging; ~65% solar share.
Moreno-Pacheco *et al.* 2024 [50]	Wind from vehicles (Mexico)	EV wind system operates ~85%; wind speeds up to 19.5 m/s.

3.1. Comparative analysis of electric vehicle-distributed generation integration architectures

Different architectural arrangements, each with unique performance characteristics, problems, and applications, can be used to integrate EVs with DG. This section addresses important implementation gaps, presents an organized comparison of popular architectures, and identifies outstanding issues. The literature-based key architectures are compiled and tabulated in Table 3. The discussion of the performance metrics is as follows:

– Renewable self-consumption: well-sized PV+ storage systems [41] are usually the next most feasible, after hybrid systems (e.g., [42] demonstrate high practicality). High rates are achievable with wind-only systems provided charging adapts dynamically to the wind's availability [30].
– Reliability and availability: hybrid systems are particularly dependable [45], whereas single-source systems (wind or PV) are more reliant on the weather and need grid/storage support to ensure availability [30], [38].
– Cost-effectiveness: research such as [39], [42] indicates that although hybrid systems are expensive initially, they may end up being more economical for off-grid applications over time since they require fewer diesel generators. Particularly in light of declining PV prices, grid-connected PV-EVCS frequently exhibit a favourable payback period [38], [40].

– Grid impact: all topologies have the potential to induce instability on the grid (voltage drops/rises [33]) in the absence of intelligent regulation. However, by offering ancillary services, the V2G Ecosystem is specially crafted to positively affect the grid [29], [32].

Table 3. Architecture-based comparison of EV-DG integration

Architecture	Key characteristics	Strengths	Limitations and challenges
PV-EVCS [25], [26], [38]-[41], [46]	– Direct or grid-assisted charging using solar PV. – Often includes stationary battery storage (BS) to buffer intermittency.	– High synergy: EV daytime charging aligns with solar peak. – Reduces grid dependency and carbon footprint. – Well-suited for commercial buildings and rooftops.	– Zero generation at night, requiring full grid/BS backup. – Highly dependent on weather and seasonal variations. – Requires significant space for PV arrays.
Wind-EVCS [30], [33], [50]	– Utilizes wind turbines to power EV charging. – Often deployed in wind-rich or remote areas.	– Can generate power day and night, offering a better capacity factor than solar. – Suitable for highway corridors and open areas.	– High visual and acoustic impact, limiting urban deployment. – Power output is highly turbulent and less predictable than PV. – Complex maintenance and higher initial cost per kW.
Hybrid renewable (PV-wind) EVCS [34], [35], [42], [45], [49]	– Combines PV and wind to leverage complementary generation profiles. – Almost always includes storage for stability.	– Significantly reduced intermittency and improved reliability. – Higher energy autonomy and reduced need for grid backup. – Optimal for off-grid or weak-grid applications.	– Highest system complexity and capital cost. – Requires a sophisticated energy management system (EMS). – Large spatial footprint for both technologies.
Grid-integrated V2G ecosystem [29], [31], [32], [35], [44], [47], [48]	– EVs and DG (any source) are connected to the main grid. – Focus on bidirectional power flow (V2G) for grid services.	– Provides grid support: frequency regulation, voltage stabilization, peak shaving. – Can absorb excess renewable generation, preventing curtailment. – Unlocks new revenue streams for EV owners.	– Most complex architecture requiring advanced communication. – Accelerated battery degradation is a major economic barrier. – Lacks standardized market and regulatory frameworks.

3.2. Key challenges in integrating electric vehicles with renewable energy sources-based distributed generation

A revolutionary route to a sustainable energy environment is presented by the cooperative integration of DG, especially from RESs like solar and wind, and EVs. But there are many complex issues with this integration that go beyond straightforward technological connectivity. Due to their close connections, these difficulties frequently form a complicated web of obstacles that requires an all-encompassing approach to overcome. These issues are divided into technological, economic, infrastructure, and social dimensions in this section. Their linkages are also discussed, along with new solutions and areas of priority research.

3.2.1. Technical challenges

The most direct obstacle is technical issues with EV loads' functional and physical connectivity with DG supplies and the current grid infrastructure.

– Renewable DG intermittency and uncertainty: PV and wind-based DG electricity production is erratic and frequently unpredictable due to the differing patterns of solar irradiance and wind speed [27], [30]. This makes it extremely difficult to balance supply with EVs' fluctuating charging needs. Operational difficulties resulting from incorrect projections of DG outputs and EV charging trends may need the addition of reserve capacity from the grid or traditional sources [28], [35].
– Grid stability and power quality concerns: unplanned, high-power EV charging can cause voltage deviations, frequency oscillations, and thermal overflowing of transmission transformers and lines, particularly when DG generation is low [29], [33]. On the other hand, reverse power flow from various sources may result in issues with voltage rise during peak DG production, above legal restrictions [27].
– The complexity of battery degradation and energy management: battery degradation is accelerated when EV batteries are used for V2G services or when stationary storage is used to buffer DG intermittency. Because Li-ion batteries' intricate electrochemical processes are sensitive to temperature, depth of depletion, and cycle patterns, scheduling that reduces degradation is extremely difficult [25], [41]. It takes a lot of computing to create real-time energy administration systems that can improve for grid support, user cost, and battery life all at once [25], [41].

- Protection and control system conflicts: blinding, false tripping, and unsynchronized islanding activities may result from the bi-directional power flow from both DG modules and V2G-enabled EVs, which might interfere with the conventional unidirectional design of safeguards (such as relays and fuses) [37].
- Forecasting and real-time control: although research like [28], [35] shows the significance of forecasting for microgrid functioning, there is a significant gap in the switch to reliable, real-time control. Many of the systems in use today depend on day-ahead scheduling. In order to improve charging/discharging decisions second-by-second, scalable, low-latency control algorithms that can manage the real-time uncertainty of both renewable energy and EV user behaviour are lacking.

3.2.2. Economic and financial challenges

One of the main obstacles to the integrated system's widespread adoption is its high lifetime and capital expenses.

- Substantial upfront capital costs: installing EV charging infrastructure using renewable DG necessitates a significant financial outlay for PV panels, wind turbines, electricity conversion systems, and frequently large-scale battery energy storage systems (BESS) in addition to EVs and chargers [38], [39], [42]. Such hybrid systems' economic feasibility is extremely dependent on government subsidies, funding rates, and component expenses.
- Battery replacement costs: the rapid wear and tear on the EV battery might reduce the financial advantages of V2G or frequent cycling for DG integration, resulting in expensive and time-consuming replacements [25]. Existing business models find it difficult to adequately reimburse EV owners for this deterioration.
- Uncertain return on investment (ROI): for utilities and charging facility operators, the ROI is dependent on many highly unpredictable factors, including shifting energy export regulations, fluctuating electricity prices, varying rates of EV adoption, and the future cost trends of both DG and storage methods [29], [42]. Private investment is discouraged by such uncertainty.
- Market design: small, dispersed assets like EVs are not well-suited for the current power markets. Developing new market frameworks or aggregator strategies that enable millions of EVs to engage in ancillary service markets profitably is an unresolved task [44], [48].
- Regulatory obstacles: in the majority of areas, laws forbid or fail to recognize a car as a grid-scale resource. A necessary but unfinished stage before broad involvement may take place is the definition of legal frameworks, settlement procedures, and grid rules for V2G [44], [47].

3.2.3. Infrastructure and planning challenges

The actual deployment of required hardware is subject to logistical and spatial limitations and necessitates meticulous strategic planning.

- Optimal location and size: to optimize local renewable energy usage, reduce grid upgrading expenses, and satisfy spatial demand patterns, the positioning and capacity of both DG units and EVCSs must be coordinated. Inadequate positioning can make grid congestion worse instead of better [27], [36]. For example, it is not desirable to place a large solar-powered charging station in a region with poor grid infrastructure or limited solar potential [27], [38].
- Standardization and interoperability: the smooth transfer of data and control signals required for smart charging and V2G services is hampered by the absence of global standards for connecting between EVs, chargers, DG systems, and grid operators. Large-scale, interoperable approaches are made more difficult by this fragmentation [44].
- Grid modernization demands: the majority of distribution networks in place were not built to handle concentrated loads from EV charging clusters or bi-directional power flows. Costly improvements to grid infrastructure, including transformers, switchgear, and advanced metering infrastructure (AMI), are required for widespread connectivity [29], [37].

3.2.4. Social and regulatory challenges

The integration of EV and DG is significantly facilitated or hindered by human behavior and legislative frameworks.

- Range anxiety and user activity: "Range anxiety"—the worry that one would be stuck with a dead battery—is a common factor in consumers' hesitation to embrace EVs. This can be mitigated by renewable charging, but it also creates "charging anxiety" about the availability of wind or sun when needed. Demand-side management efforts are made more difficult by the typical charging behavior of users, which frequently does not correspond with DG accessibility [40], [46].

– Complication of tariff structures and market regulations: tariff structures need to be straightforward and financially appealing for customers to actively engage in V2G or smart charging. While real-time pricing and time-of-use (TOU) can encourage charging during DG surplus periods, their intricacy may hinder customer involvement [44], [48]. Additionally, in the majority of regions, clear market processes for EVs to offer services directly to the grid remain lacking.
– Regulatory and policy barriers: antiquated laws may forbid or discourage the selling of power from private DG systems to EV customers or back to the grid. Important regulatory actions that are still being taken in many countries include streamlining permission procedures, creating clear technological standards, and setting reasonable pay rates for V2G (such as net metering regulations for EVs) [44], [46].

3.3. Trade-offs in electric vehicles distributed generation integration

Strategic compromises characterize the integration of DG and EVs. The decision between a centralized and decentralized approach depends on where operational control is valued over grid resilience and user convenience. Every choice essentially involves navigating an essential cost-reliability trade-off: robust, independent systems demand a large capital investment, whereas simpler, grid-leaning solutions are less expensive but more vulnerable. The Trade-Offs in EV and DG integration is listed in Table 4. The HC trade-off must be actively managed to scale this integration successfully. Growth will be slowed by passive infrastructure; therefore, in order to avoid expensive physical modifications, smart grid innovations and coordinated control are required. Moreover, overcoming the economic conflict between grid income and battery lifespan is necessary to fully realize the potential of V2G. In order to ensure that the market can develop without becoming fragmented, it is ultimately necessary to strike a balance between standardization for interoperability and flexibility to stimulate innovation. The ideal course is context-specific and dictated by local grid limits, resources, and policy objectives; there is no one-size-fits-all option.

Table 4. Trade-offs in EV and DG integration

Trade-off dimension	Option A	Option B	Key implications
Infrastructure model [29], [38], [46], [51], [53]	Centralized charging hubs	Decentralized charging	A provides easier grid service delivery and economies of scale, but it also runs the danger of causing significant grid congestion. B presents a huge, intricate control task yet provides users with simplicity and distributed load. The best model is a hybrid one.
System design [40], [42], [45], [54]	Low-cost, grid-dependent	High-reliability, stand-alone	Simple grid-tied PV, or A, has a minimal capital expenditure but no resilience in the event of an outage. Although B (with storage/hybrid DG) has a substantial capital expenditure, it guarantees dependability and energy independence. This is a clear trade-off between resilience and capital.
Grid integration [27], [29], [32], [53]	Passive (no investment)	Active (grid modernization)	Although A is inexpensive, it significantly restricts HC, which inhibits the expansion of EV/DG. Although it necessitates a large investment, B (smart inverters, control, improvements) raises HC and permits more penetration.
V2G service provision [25], [47], [48], [54]	Maximize grid revenue	Minimize battery degradation	A speed up battery wear while optimizing frequency regulation's short-term revenue. B loses out on possible revenue but safeguards the battery asset. Degradation quantification and compensation are the main challenges.
Technology ecosystem [44], [52]	Standardization	Innovation	A (such as ISO 15118) is essential for plug-and-play ecosystem growth and interoperability. B makes it possible to quickly enhance features. Progress in technology and stability/compatibility are traded off.

3.4. Future research directions and emerging paradigms

The existing literature not only lists difficulties but also clearly defines a path for further study and advancement. Bidirectional charging, artificial intelligence (AI), and sophisticated grid modelling, when combined, have the potential to turn EV-DG integration from a problem into a vital component of a robust, decarbonized energy system.

a. Next-generation bidirectional charging (V2X): although V2G is a well-established idea, it will develop further than just returning energy to the grid. A more comprehensive V2X ecosystem is suggested by the references.

– Pay attention to models of battery degradation and compensatory mechanisms: creating widely recognized, real-time battery deterioration models that can be incorporated into EMS is a top research priority [25], [54]. In order to make V2X economically feasible for all parties involved, future research must concentrate on developing standardized procedures to measure the wear and tear from V2X cycles and establishing equitable market-based compensation mechanisms [47], [48].
– Growth of V2X applications: in addition to grid frequency regulation, research will focus on localized microgrid services, which use a combination of EVs to stabilize islanded microgrids, facilitate black-starting, and improve resilience after main grid failures [37], [45].

1) Virtual power plants (VPPs): creating scalable aggregation infrastructure to combine thousands of DG units and EVs into a dispatchable resource that can take part in commercial energy markets [44], [47].
2) To maximize freedom from the grid, particularly during periods of peak cost, V2H, and vehicle-to-building (V2B) systems are optimized for daily self-usage of rooftop solar, using the EV battery as a buffer [41], [46].

b. Predictive and AI-driven smart EMS: by utilizing AI and machine learning to optimize proactive, predictive optimization, EMS will transition from responsive or schedule-based control.

- Hybrid forecasting models: to significantly increase the precision of short-term (minute-ahead) solar and wind production forecasts, future EMS will rely on sophisticated hybrid forecasts that include past patterns, real-time sky imagery, and numerical climate prediction (NWP) data [28], [35]. Furthermore, using user profiles and historical data, AI models will be able to more accurately forecast EV user behavior (such as arrival and departure times and energy requirements) [48].
- Multi-objective optimization for real-time control: the study will concentrate on creating AI algorithms that are lightweight and able to perform multi-objective optimization in real time. In addition to reducing energy costs, these systems will also optimize for battery health, renewable self-use, grid restrictions (voltage, frequency), and user comfort [25], [32], [35]. One important enabler in this regard is the incorporation of blockchain technology for transparent, automated P2P energy trade and payment [43].
- Universal interoperability protocols: one important avenue is the creation and widespread implementation of open communication standards (such as ISO 15118 and open charge point protocol (OCPP)), which guarantee smooth plug-and-play compatibility between any EV, charger, DG system, and grid operator. This is crucial for the expansion of smart EMS [52].

c. Improving grid resilience and HC: to optimize the HC of current grids without requiring unaffordable infrastructure modifications, future research will concentrate on dynamic solutions.

- Dynamic HC evaluation: creating real-time dynamic HC tools by going beyond static, restrictive grid models. In order to enable more effective and secure integration, these tools would continuously determine the available space for new EV and DG connectivity at any given node and time using grid sensor data and state estimation [53].
- EVs as resources for grid resilience: formally including EVs and DG into grid planning as resilience assets rather than just loads is a substantial paradigm change. This comprises:

1) Developing new technical standards that specify how EVs should react to grid disruptions (such as fault ride-through and voltage support) is known as "formulating grid codes for V2G" [44], [54].
2) Resilience-oriented scheduling: developing scheduling techniques that, in advance of severe weather conditions or grid emergencies, pre-position energy in EV batteries to guarantee that vital infrastructure can be powered during blackouts [31], [37].

- Holistic system design and policy approaches: a systemic method that integrates policy analysis and techno-economic models is becoming more and more necessary in research. To encourage investments in V2X and compensate customers for supplying the grid with resilience services, further research will identify the best laws and regulations, tariff structure, and market processes (such as distribution-level markets) [44], [47], [54].

In summary, the future of EV-DG integration is smart, mutually beneficial and focused on resilience. The main strategies include using AI to unlock value, developing standards to facilitate scaling, and changing planning paradigms to see EVs as one of the most distributed and adaptable assets available for constructing the sustainable grid of the future, rather than as a burden on the grid.

4. CONCLUSION

The integration of EVs with DG based on renewable energy, mainly solar PV and wind power, has been thoroughly examined in this research. Our approach critically examines the deep interdependencies and trade-offs that characterize this subject, going beyond a straightforward technological overview. The analysis demonstrates that although the technological viability of a number of architectures—from sophisticated hybrid and V2G systems to rooftop solar charging—has been proved in the literature, a complicated web of obstacles prevents their widespread use. These are not distinct but rather intricately linked: even the most technically sound solutions may be thwarted by social barriers like user acceptance and regulatory lethargy, while the technical difficulty of renewable intermittency exacerbates economic obstacles by necessitating storage. Context-specific solutions are required instead of a one-size-fits-all strategy due to crucial trade-offs between infrastructure centralization and decentralization, as well as between system cost and reliability. The biggest scalability obstacles are no longer just technical. Instead, problems are found in the fields of economics (how to measure and compensate for battery degradation in V2G), interoperability, and policy. As a result, addressing these practical implementation challenges must be the main focus of future research and directions. creating predictive, AI-driven EMSs that optimize grid support, cost, and battery health in real time. In conclusion, one of the main pillars of the smart grid transition is the effective integration of EVs and RES-based DG. It will take a coordinated, multidisciplinary effort to overcome its obstacles, treating the EV as a vital active element in creating a more robust, intelligent, and sustainable energy environment rather than as a passive load.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
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Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [MA], upon reasonable request.

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