

# Electric Vehicle Integration with Smart Grids: A Comprehensive Review of Renewable Energy Integration for Future V2G Systems

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## ABSTRACT

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This paper provides a comprehensive review of recent advancements in the interaction between electric vehicles (EVs) and smart grid systems, highlighting their potential to shape the future of intelligent and sustainable power networks. The integration of EVs into the smart grid introduces new opportunities for grid support while also presenting challenges related to infrastructure, communication, and control coordination. Following an in-depth review of modern smart metering and communication technologies, various strategies for effective EV integration are analysed. Smart charging and vehicle-to-grid (V2G) technologies are critically examined in terms of their potential benefits, technical limitations, and operational impacts on grid stability. Beyond summarizing existing approaches, this review identifies a key non-obvious conclusion that many reported V2G benefits are constrained not by converter or control capabilities, but by the misalignment between battery degradation models, user mobility assumptions, and grid-level optimization frameworks. Moreover, as renewable energy sources (RES), such as photovoltaic and wind power, achieve higher penetration levels, their inherent intermittency raises new concerns for system reliability and power quality. EVs, when properly managed, can mitigate these fluctuations through intelligent scheduling and bidirectional energy exchange, provided that realistic availability and degradation-aware coordination are incorporated. The paper also explores current research trends in renewable EV integration, identifying key challenges and open research gaps, and emphasizes the role of coordinated EV-grid integration, advanced control, and robust communication frameworks in enabling the large-scale deployment of V2G systems in future smart and resilient power networks.

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## 1. Introduction

Fossil fuels continue to dominate the global energy landscape, particularly in the transportation and electricity generation sectors. However, their finite reserves and adverse environmental impacts necessitate an urgent transition toward sustainable alternatives. The accelerating adoption of electric vehicles (EVs) is reshaping energy demand patterns and coupling mobility with electricity sectors, offering opportunities for grid support and flexibility through V2G technologies. Recent global energy assessments indicate that oil demand is reaching a peak, with a potential decline expected by the end of this decade due to electrification and clean mobility trends [1]. According to the International Energy Agency (IEA), global oil consumption growth slowed to 0.8% in 2024, the lowest in recent decades, primarily driven by the rapid adoption of electric mobility and improved energy efficiency measures [2]. The U.S. Energy Information Administration (EIA) further projects that Brent crude oil prices will remain within the range of USD 50–65 per barrel by 2026, reflecting a stable yet constrained supply demand balance [3].

The transportation sector remains the largest consumer of petroleum-based fuels, accounting for over 57% of total global oil demand in 2025 [4]. However, the accelerating adoption of EVs is reshaping this scenario. In the United States alone, more than 1.56 million EVs were sold in 2024, representing approximately 10% of all new light-duty vehicle sales [5]. The coupling between the mobility and electricity sectors is becoming increasingly significant as EVs emerge not only as consumers of electrical energy but also as potential contributors to power system flexibility. Globally, the V2G technology market was valued at USD 3.45 billion in 2023 and is projected to grow at a compound annual growth rate (CAGR) of 26.6%, reaching nearly USD 17.9 billion by 2030 [6]. Other forecasts suggest even higher growth, anticipating a 38% CAGR from 2025 to 2034 [7]. This expansion highlights the growing recognition of EVs as active participants in grid operations, capable of supporting energy balancing and ancillary services.

Transitioning from ICEVs to EVs offers multifaceted benefits, including decarbonization, enhanced grid integration, and improved system flexibility. Although EVs introduce additional demand on the grid, they provide substantial energy storage potential, as studies estimate that vehicles remain parked nearly 95% of the time [8]. This idle capacity can be strategically utilized under the V2G concept, enabling EVs to discharge stored energy to the grid when required. V2G-enabled fleets can deliver ancillary services such as peak shaving, spinning reserves, and voltage or frequency regulation, thereby enhancing grid stability and resilience [9]. Simultaneously, the increasing penetration of variable renewable energy (VRE) sources, such as wind and PV systems, has introduced new challenges related to intermittency and forecasting uncertainties. Large-scale integration of renewables requires flexible storage systems to ensure reliable and continuous operation. In this regard, aggregated Electric vehicle (EV) fleets can act as distributed energy storage assets within the framework of virtual power plants (VPPs), coordinating charging and discharging activities to maintain grid stability and optimize power flows [10].

Nevertheless, integrating EVs into the power system presents technical and economic challenges. From the utility's perspective, EVs function as stochastic loads and potential power sources, complicating system planning and operation [11]. Issues such as demand forecasting, voltage management, and power flow regulation require sophisticated control strategies [12]. From the vehicle owner's perspective, participation in V2G programs must offer tangible economic incentives while accounting for factors like battery degradation and operational costs. Transparent and optimized bidirectional energy transaction schemes covering real-time pricing, scheduling, and incentive mechanisms are therefore essential. Furthermore, aggregators must continuously monitor fleet parameters, including the state of charge (SoC), driving behaviour, and battery capacity, to participate effectively in ancillary service markets and demand response programs [9].

The evolution of deregulated power markets, supported by advanced metering infrastructure (AMI) and information and communication technologies (ICT), is accelerating the emergence of smart grids. These modernized grids facilitate real-time pricing, dynamic control, and two-way power flow,

creating an ideal environment for integrating EVs and V2G systems. Smart charging strategies, whether unidirectional (smart charging) or bidirectional (V2G-enabled), can mitigate grid stress, reduce peak demand, and improve energy utilization efficiency [13], [14]. Recent modelling studies indicate that when approximately 25–35% of EVs participate in bidirectional (V2G) charging, overall system operation costs can be reduced by around 10–15% and peak demand by up to 20% compared to unidirectional smart charging strategies, depending on renewable penetration and market conditions [15], [16].

While previous studies have highlighted aspects of EV–grid interaction, gaps remain. For example, studies using IEA and EIA data [1]–[3] focus on EV adoption trends and energy demand but do not comprehensively address technical control strategies for V2G integration. Market and economic aspects have been discussed in modelling studies [15], [16], yet these works often overlook the combined role of ICT infrastructure and smart charging for coordinated EV fleet management. Similarly, V2G benefits under high renewable penetration [6], [7] are identified, but prior reviews do not integrate operational, economic, and technical perspectives in a single framework. In contrast, this paper provides a holistic review covering control strategies, market mechanisms, smart charging, and virtual power plant frameworks, bridging these previously isolated aspects.

Given the rapidly evolving landscape of energy systems and electric mobility, developing a comprehensive understanding of EV–grid interaction mechanisms are critical. This paper provides an extensive review of recent advancements in EV integration with smart grids, focusing on V2G technology, control strategies, and market mechanisms. It highlights emerging trends, identifies key challenges, and outlines potential research directions to advance EV participation in grid services. Both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are considered under the broad EV category for this study.

The remainder of this paper is organized as follows. [Section 2](#) presents literature procedure. [Section 3](#) reviews the integration of EVs into modern power systems under the V2G concept and its realization within VPP frameworks. [Section 4](#) discusses smart charging approaches and supporting ICT infrastructure for coordinated EV grid interaction. [Section 5](#) examines the synergy between EVs and renewable energy systems, while [Section 6](#) evaluates practical feasibility, case studies, future perspective and global trends of V2G implementation. Finally, [Section 7](#) presents concluding remarks.

## 2. Review Methodology

A structured literature review methodology was adopted to ensure systematic coverage and minimize selection bias, guided by the core principles of established systematic review practices, including PRISMA. The review focuses on EV integration with smart grids, V2G technologies, smart charging strategies, and renewable energy coordination. Literature searches were conducted across IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, and Google Scholar, targeting peer-reviewed journal articles, conference papers, and authoritative technical reports published mainly between 2020 and 2025. Search strings combined terms such as electric vehicle, vehicle-to-grid, smart charging, EV aggregation, renewable energy integration, and smart grid control. A multi-stage screening process was applied. Titles and abstracts were first screened to remove duplicates and out-of-scope studies, followed by full-text assessment to retain publications with quantitative analysis, system-level modelling, experimental validation, or large-scale pilot implementations.

## 3. EV Integration into Modern Power System

The integration of large-scale EVs fleets into modern power systems introduces both technical challenges and economic opportunities. Recent research emphasizes that uncoordinated charging patterns can significantly aggravate power quality issues, including transformer overloading, feeder congestion, voltage fluctuations, and peak demand escalation [13], [17]. Conversely, coordinated and bidirectional charging approaches, such as V2G and vehicle-to-home (V2H), can provide valuable

ancillary services namely peak shaving, load balancing, and frequency regulation, thereby enhancing system efficiency and flexibility [18].

The majority of EV charging events currently occur in residential settings due to user convenience and lower electricity tariffs; however, the proliferation of public, workplace, and fast-charging stations is expected to accelerate with increasing EV adoption [19]. The consequences of widespread charging extend to local distribution networks, where additional infrastructure investments may be required to maintain reliability. Nevertheless, when properly coordinated through smart charging and aggregator-based control mechanisms, large-scale EV integration can yield improvements in grid stability, renewable energy utilization, and overall system efficiency [20].

To achieve these benefits, several integration architectures have been proposed in recent literature. The aggregator-based model has gained prominence as it provides an intermediary framework between EV owners, distribution system operators (DSOs), transmission system operators (TSOs), and energy markets [21]. Aggregators optimize the collective charging and discharging schedules of EV fleets to provide grid services and participate in electricity markets. Similarly, the VPP concept allows EVs to operate as aggregated distributed energy resources (DERs) under centralized or hierarchical coordination, providing ancillary services such as frequency control and spinning reserve [10]. On the other hand, decentralized integration frameworks enable individual EVs to respond autonomously to dynamic pricing signals or demand response programs [22]. Although decentralized systems promote user flexibility, they also increase communication complexity, cybersecurity risks, and uncertainties in energy forecasting [23].

Battery degradation remains a central challenge in large-scale V2G deployment. Extensive cycling during V2G operations accelerates electrochemical wear mechanisms, thereby affecting both capacity retention and power capability. Recent studies have highlighted the relationship between charging behaviour, degradation mechanisms, and battery lifetime in both EVs and stationary Battery Energy Storage Systems (BESS). An online V2G charging scheduling strategy was proposed in [24], the practical deployment train-flow cycle counting method for real-time battery aging estimation, which achieved an 8.4% reduction in equivalent full cycle count while minimizing grid fluctuations. In [25], a dynamic modelling approach based on realistic driving cycles demonstrated that fast charging at 50 kW reduces Li-ion battery lifespan by approximately 17% compared to 22 kW AC charging. Similarly, a semiempirical electrothermal aging model for Li-ion nickel–manganese–cobalt (NMC) cells were presented in [26], revealing that participation in V2G services increases charge throughput from 120,000 Ah to 230,000 Ah, resulting in a two-year reduction in battery lifespan. Moreover, an accelerated lifetime estimation model for LiFePO<sub>4</sub> batteries used in grid-scale BESS was proposed in [27], incorporating parameters such as temperature, SoC, and depth of discharge, and validated on a 500 kW/250 kWh system in Puducherry, India.

Collectively, these studies provide valuable insights into battery degradation modelling and optimization strategies for extending the lifespan of both mobile and stationary ESS. However, a critical comparison across these models indicates that degradation predictions are highly dependent on underlying assumptions, operating profiles, and battery chemistries, making direct accuracy ranking difficult. Empirical and semiempirical models offer practical applicability for real-time V2G scheduling, while physics-informed approaches provide deeper insight into aging mechanisms but require extensive parameterization and experimental validation. Although recent studies on solid-state batteries suggest improved cycling stability, large-scale experimental evidence under realistic V2G operating conditions remains limited, and therefore their potential to fully mitigate degradation concerns cannot yet be conclusively established.

Recent developments also highlight the importance of advanced ICT and smart grid infrastructure to facilitate efficient EV-grid interactions. Real-time two-way communication between aggregators, grid operators (GOs), and EV owners is essential for exchanging data on pricing, demand forecasts, and driving behaviour [28]. Emerging control techniques such as deep reinforcement learning (DRL), hierarchical multi-agent coordination, and predictive scheduling are being applied to optimize energy

dispatch while considering uncertainties in renewable generation and battery health [29]. Table 1 presents the current battery technologies used by various automotive manufacturers.

To achieve this, real time advanced communication plays a crucial role in facilitating the exchange of information such as pricing signals, energy forecasts, and EVs driving behaviours among all stakeholders. Therefore, the smart grid platform is essential for ensuring the effective operation of such systems. In a smart grid environment, advanced communication infrastructure enables seamless data access, making it a key enabler for large scale integration of EVs into the energy market. The following sections present a detailed review of EVs to smart grid interaction scenarios.

**Table 1.** Comparative analysis of battery technologies and capacities among major EVs manufacturer

S/N	Car model / EV type	Battery chemistry	Capacity (kWh)	Model year
1	Tesla Model S / BEV [30]	Lithium Nickel Cobalt Aluminum Oxide (NCA)	100	2025
2	Nissan Leaf / BEV [31]	Lithium Manganese Oxide and Lithium Nickel Manganese Cobalt Oxide (LMO-NMC)	40	2024
3	BYD Seal 6 (Qin L EV) / BEV [32]	Lithium Iron Phosphate (LFP, Blade)	56.6	2024
4	XPeng P7+ / BEV [33]	Lithium Iron Phosphate (LFP)	60.7/76.3	2025
5	Fiat 500e / BEV [34]	Lithium Nickel Manganese Cobalt Oxide (NMC)	42	2024
6	Geely EX5 / BEV [32]	Lithium Iron Phosphate (LFP)	49.5/60.2	2024
7	MG4 EV / BEV [35]	Lithium Iron Phosphate (LFP) / Semi-solid Lithium Battery	64/77	2025
8	Voyah Passion / PHEV [36]	Lithium Nickel Manganese Cobalt Oxide (NMC)	43	2024
9	Lucid Air / BEV [35]	Lithium Nickel Manganese Cobalt Oxide (NMC)	88/112	2025
10	Buick Velite 6 / PHEV [37]	Lithium Nickel Manganese Cobalt Oxide (NMC)	9.5	2024

### 3.1. EV Charging Technologies and Grid Integration

EV charging represents one of the most fundamental components of modern electric mobility and its integration into power systems. Charging processes are categorized into multiple levels based on their power capacity and duration, reflecting either slow or fast charging scenarios. These standardized levels ensure compatibility across diverse EV platforms and infrastructure. In general, slow charging, typically requiring up to 8 hours for PHEVs or 20 hours or more for BEVs, is commonly implemented in residential or workplace settings. In contrast, fast charging, which ranges from approximately 15 minutes to 1 hour, is usually provided at commercial or public charging stations [38], [39]. As summarized in Table 2 [40], AC Level 1 charging is primarily designed for residential environments, whereas AC Level 2 is more suitable for semi-public or commercial facilities such as offices, parking complexes, and shopping centers. On the other hand, DC fast charging (DC Levels 1 to 3) is envisioned for widespread deployment in public and private charging stations [41].

The charging power delivered to an EV battery is predominantly determined by the charger's nominal ratings and the vehicle's battery voltage. In most modern designs, EV battery systems operate at nominal voltages up to 800 VDC in some latest platforms, though many remain around 400 VDC [42]. The total charging time depends on both the energy capacity of the battery pack and the selected charging level, which governs voltage and current limits. While the standardization of fast-charging protocols remains under discussion, its necessity is evident due to the increasing demand for shorter charging durations. Recent collaborations among global automotive manufacturers and the Society of Automotive Engineers (SAE) have led to the development of the SAE Combo standard, an integrated charging interface that accommodates AC single-phase, AC three-phase (fast AC), and ultra-fast DC charging modes. Similarly, the CHAdeMO protocol, initiated by the Tokyo Electric Power Company (TEPCO), has achieved widespread market acceptance and remains one of the most reliable fast charging technologies [41]. Such advancements are expected to enhance EV adoption by replicating the convenience of internal combustion engine vehicles (ICEVs) refuelling. For instance, V2G functionality can be supported via DC fast charging, with DC Level 1 offering up to 36 kW, Level 2 reaching 90-120 kW, and CHAdeMO-based systems delivering up to 62.5 kW. Their work highlighted

the technical feasibility of integrating V2G through existing DC fast-charging infrastructure, while also considering AC Level 1 and 2 schemes for comparative analysis [43].

**Table 2.** Technical characteristics of AC/DC charging levels defined by the SAE J1772 standard

Power level type	Voltage level (V)	Current capacity (A)	Power capacity (kW)	Remarks
AC Level 1	120	12-16	1.4-1.9	<ul style="list-style-type: none"> <li>• 1-phase supply (EV contains on-board charger)</li> <li>• suitable for residential charging</li> <li>• Charging time (approx.) PHEV: 7 h                      BEV: 17 h</li> <li>• 1 or 3-phase supply (EV contains on-board charger)</li> </ul>
AC Level 2	208-240	< 80	< 19.2	<ul style="list-style-type: none"> <li>• Common for public or commercial chargers.</li> <li>• 3.3 kW charger PHEV: 3-4 h                      BEV: 7-8 h</li> <li>• 7 kW charger PHEV: 1.5 h                      BEV: 3.5 h</li> </ul>
AC Level 3	480	-	>50	<ul style="list-style-type: none"> <li>• Under development</li> <li>• DC supply (EVSE contains off-board charger)</li> </ul>
DC Level 1	200-500	< 80	< 40	<ul style="list-style-type: none"> <li>• Typically, 20-40 kW systems</li> <li>• 20 kW charger PHEV: 20-30 min                      BEV: 1-1.5 h</li> </ul>
DC Level 2	200-1000	< 200	< 200	<ul style="list-style-type: none"> <li>• 50-200 kW systems widely used in public charging networks</li> <li>• 45 kW charger PHEV: 10 min                      BEV: 20 min</li> </ul>
DC Level 3	Up to 1000	< 400	< 400	<ul style="list-style-type: none"> <li>• Under development</li> </ul>

Despite the increasing interest in DC fast charging, its implementation presents several technical and economic challenges. As the power grid primarily operates on AC, a high-power rectifier stage is required to convert AC to DC for EV battery charging. However, the rectifier's power capability is constrained by cost, efficiency, and thermal limitations. The high current and voltage requirements of DC fast charging, as indicated in Table 2 [40], significantly influence the design size and thermal management of rectifier circuits, thereby impacting system cost and spatial footprint. Literature discussing the technical feasibility and long-term economics of DC fast charging remains limited. Nonetheless, this technology is anticipated to become the dominant charging solution in the coming decade, transforming charging stations into facilities resembling conventional fuel stations. The major challenge lies in addressing the high instantaneous power demand, the corresponding grid support infrastructure, and the potential degradation of battery lifespan. Therefore, detailed feasibility and performance studies are essential to assess the integration of DC fast-charging infrastructure within future V2G networks.

The revised SAE J1772 standard, released in January 2024 [40], introduced enhanced provisions to facilitate bidirectional energy flow, enabling both charging and discharging of EV batteries within smart grid frameworks. The revision expanded the scope of DC fast-charging levels, defined requirements for electric vehicle supply equipment (EVSE), and standardized communication protocols for PHEVs supporting reverse power flow. Complementary guidelines are provided in the National Electrical Code (NEC) Article 625 and IEC 62196, which detail electrical safety, connector configurations, and grounding standards. Technological advances in bidirectional converters with low electromagnetic interference (EMI) are increasingly supporting V2G-compatible charging, positioning such designs as the emerging standard for future EV platforms. Fig. 1 and Fig. 2 schematically illustrate AC (Levels 1 and 2) and DC (Levels 1 and 2) charging configurations,

respectively. In AC charging modes, the EVSE supplies alternating current to the onboard charger, whereas in DC configurations, the EVSE delivers direct current directly to the battery, bypassing the onboard rectifier.

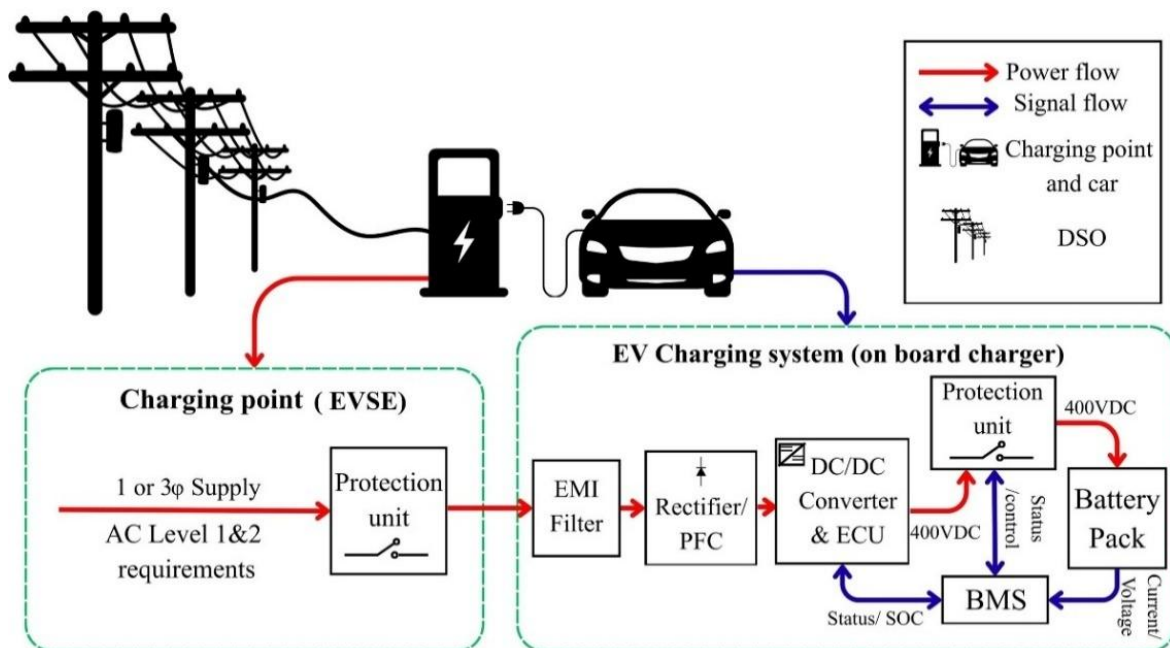


Fig. 1. Configuration of AC level 1 and level 2 EV charging setups utilizing onboard chargers [40]

Considering a typical 60 kWh battery pack, such as modern mid-range BEVs, the energy consumed during a single full charge is comparable to the daily electricity usage of an average household in Europe or North America. When multiple EVs are simultaneously connected, the cumulative energy demand can significantly increase, imposing additional stress on existing distribution grids. A study in [44] highlighted that a 3.3 kW charger operating at 220 V/15 A could elevate the household current demand by 17 to 25%. To address these implications, various charging schemes have been developed based on user behaviour and grid operating conditions, including uncontrolled charging, dual-tariff charging, and intelligent charging. In uncontrolled charging, the EV begins charging immediately upon connection, leading to peak demand surges. Numerous studies have demonstrated that such uncoordinated charging can exacerbate grid congestion and increase the capital costs of distribution network upgrades [45].

The impact of EV charging is most prominent at the distribution level, where unregulated load growth accelerates equipment aging and risks protective device tripping under overload conditions. In [46], implementing coordinated smart charging strategies could reduce incremental investment in distribution infrastructure by approximately 60 to 70%. Moreover, by shifting charging demand to off-peak hours or through dynamic scheduling, utilities could avoid 5 to 35% of infrastructure investment costs, while potentially reducing energy losses by up to 40% [47]. These findings underscore the necessity of intelligent, coordinated charging strategies to ensure the reliable and sustainable integration of EVs into future power grids.

### 3.2. EV Integration with V2G System Architecture

EVs can be effectively integrated into modern power systems to serve multiple operational objectives. Depending on their mode of operation, EVs can function as dynamic loads by drawing energy from the grid during charging periods or as dynamic energy storage systems (ESS) by discharging stored energy back to the grid. The latter operation mode, widely known as V2G, enables bidirectional power exchange between EVs and the electric grid. However, individual EVs are often limited in their storage capacity, spatial distribution, and availability, which restricts their standalone ability to provide significant grid services. To overcome these limitations, large numbers of EVs are

typically aggregated and coordinated under specific control schemes and operational objectives to realize the V2G concept effectively [9]. When aggregated, EV fleets can be treated as controllable DERs capable of participating in electricity markets and providing essential grid support functions such as load balancing, voltage regulation, and frequency stabilization. Fig. 3 VPP control and implementation in the V2G context, where the EV aggregator functions as a virtual power plant. The charging management system communicates vehicle status (SOC/power availability) to the VPP control center, which manages energy dispatch and coordination between grid operators and market participants.

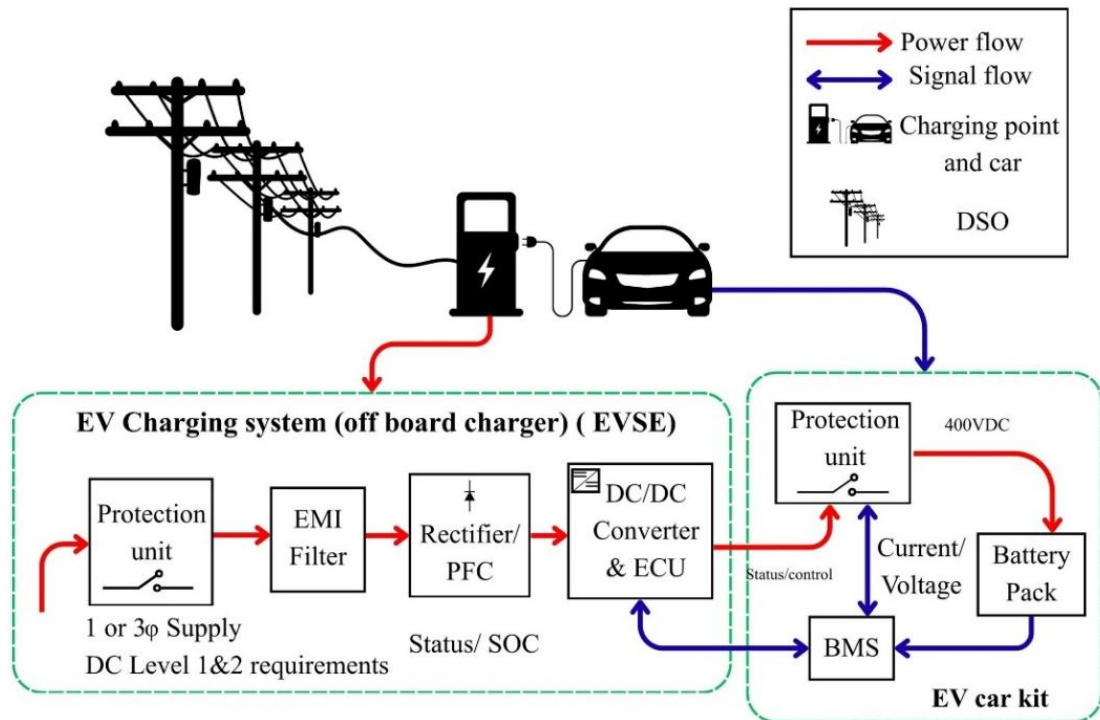


Fig. 2. Configuration of DC level 1 and level 2 EV charging frameworks utilizing off-board chargers [40]

The interaction between EVs and the smart grid can occur through two main configurations: bidirectional and unidirectional power flow. In the bidirectional setup, energy can flow both from the grid to the EV (charging) and from the EV back to the grid (discharging), enabling V2G operation. Numerous studies have examined the economic feasibility and operational benefits of this two-way interaction between aggregated EV fleets and the power grid [48]. Despite its advantages, bidirectional power flow introduces technical and economic challenges, including the need for advanced safety protections (e.g., anti-islanding measures), complex metering infrastructure, and higher system costs, which may reduce its overall economic attractiveness. Conversely, the unidirectional configuration allows energy transfer only from the grid to the EV, restricting the system to charging operations [44]. Even within this limitation, EVs can still contribute to the energy market and provide ancillary services such as voltage and frequency regulation.

Recent studies have provided a more comprehensive understanding of the techno-economic balance between unidirectional and bidirectional charging configurations in V2G applications. Research conducted in [49], [50] indicate that bidirectional systems offer greater flexibility for ancillary grid services, particularly in frequency regulation, spinning reserve, and renewable power smoothing. However, their overall economic advantage remains highly dependent on market dynamics and infrastructure investment. On average, BC-enabled EVs generate approximately 10–20% higher grid service revenue than unidirectional systems, with regulation power capacities typically reported between 5 and 7 kW for a 20–25 kWh battery module [51]. These systems also exhibit battery degradation rates up to 8–10% higher than those of unidirectional configurations due to increased cycling stress [49], [52].

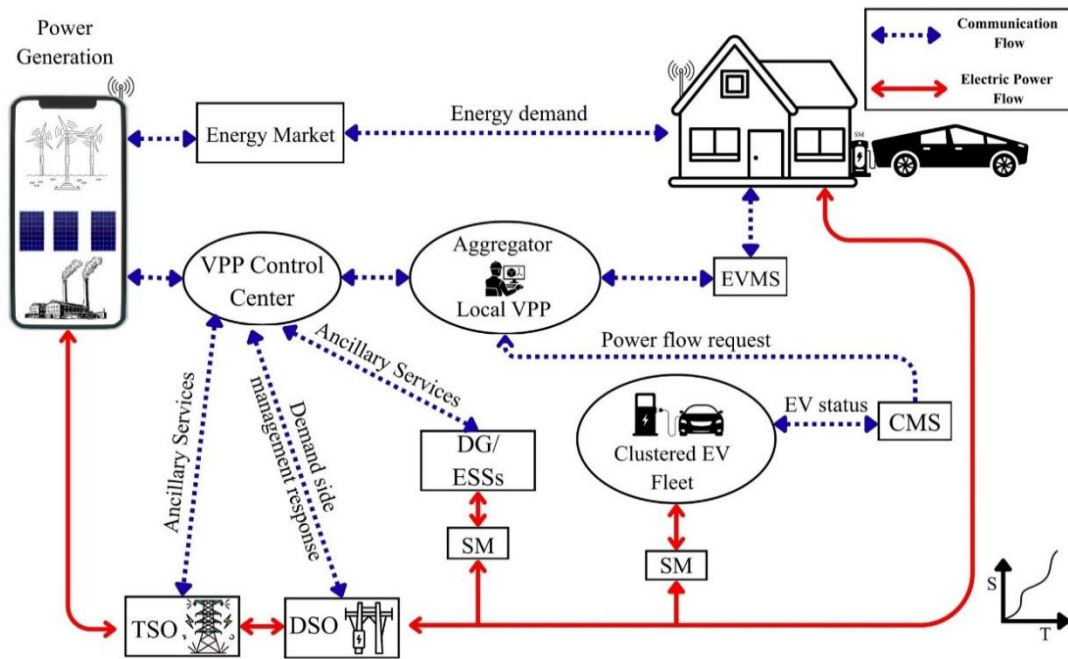


Fig. 3. Realization and control architecture of a virtual power plant in the vehicle-to-grid context [9]

In contrast, unidirectional systems, although limited to one-directional energy transfer, demonstrate 30–40% lower implementation and maintenance costs, longer battery lifetime, and simpler communication requirements [50], [53]. Grid studies conducted in Ontario, Canada, have shown that nearly 500,000 EVs can be integrated using existing unidirectional infrastructure without the need for additional investment, which highlights their scalability under current grid conditions [50]. Overall, while bidirectional operation continues to play a critical role in enabling advanced grid-support functions, optimized unidirectional frameworks that incorporate intelligent scheduling and demand-response strategies can achieve 70–85% of the functional and economic benefits of bidirectional systems at substantially lower lifecycle costs. This finding underscores the potential of unidirectional configurations as a practical and cost-effective transitional approach toward large-scale V2G integration [51], [54].

#### 4. Smart Grid Infrastructure for EV Integration

The increasing penetration of DERs is transforming the landscape of power generation and distribution. DERs introduce spatial and temporal variability in both power production and consumption, thereby increasing the complexity of energy management within traditional power grids. To address these challenges, the concept of the smart grid has emerged as a modernized solution that enhances the flexibility, efficiency, reliability, and security of power systems. The smart grid integrates advanced communication technologies, intelligent metering, and sophisticated control mechanisms, enabling dynamic interaction among various energy stakeholders. Within this framework, EVs function not only as variable loads but also as potential dispatchable distributed energy sources, offering greater flexibility and optimization in power system operation [55].

Extensive research has been undertaken to evaluate and develop smart grid infrastructures that support large-scale EV integration into the energy market. A central focus of these efforts is the standardization of technologies and communication protocols for electric power distribution, which serves as a foundation for establishing an interactive and interoperable smart grid. Recent standards and technical specifications have been introduced to ensure seamless connectivity and interoperability between EVs and the grid [13], [28].

Furthermore, EVs, through the Electric vehicle management (EVM) system, can exchange data with grid GOs or aggregators, enabling efficient coordination and control. The EVM often

incorporates smart meters (SMs) as a core component to facilitate real-time energy measurement, communication, and control. By leveraging bidirectional data exchange, smart scheduling mechanisms can be implemented to optimize grid power utilization based on the real-time impact of EV charging activities, thereby ensuring more efficient and balanced grid operation [28], [56].

#### 4.1. Smart Charging Strategies and Control Framework for EV

Uncontrolled charging of EVs can exacerbate transformer loading, increase peak demand, and degrade power quality, which has prompted extensive research into smart charging strategies to mitigate these impacts. A major body of work focuses on developing interoperable communication infrastructures that enable coordinated charging across residential, commercial, and aggregator domains, while other studies design real-time and optimization-based control schemes to minimize costs and alleviate network stress. Multi-agent and learning-based methods have been widely explored as effective coordination frameworks for distributed charging control. For example, a multi-agent DRL framework for real-time multi-home energy management achieved an average reduction of approximately 9% in household energy consumption compared to uncontrolled scenarios and demonstrated significant improvements relative to simple time-of-use pricing [57].

Probabilistic analyses incorporating transformer thermal ageing models further reveal that unmanaged EV charging can accelerate insulation degradation and reduce transformer lifespan. Coordinated scheduling with demand management, on the other hand, has been shown to mitigate these effects, lowering equivalent ageing indices and prolonging asset longevity under diverse operating conditions [58]. Model Predictive Control (MPC) inspired methods implemented at both charging station and MG levels have demonstrated substantial reductions in local power peaks, typically ranging from 15% to over 50%, depending on fleet size, charging power, and user flexibility. These control strategies have also been shown to enhance the reliability and adaptability of charging networks in real-world scenarios [59].

At the distribution level, comprehensive reviews consolidating numerous case studies have confirmed that coordinated and bidirectional charging operations can significantly improve voltage stability and reduce line losses. In favourable conditions, such strategies have been observed to increase minimum bus voltages from approximately 0.88 p.u. to around 0.94 to 0.95 p.u., contributing to improved grid performance and reliability [13]. Collectively, these published findings underscore that intelligent and well-coordinated EV charging architectures, supported by standardized communication protocols, SMs, and EVM systems, can alleviate grid stress, lower operational costs, and extend equipment lifetime as EV adoption scales.

#### 4.2. Advanced Metering Infrastructure for EV Integration

The deployment of AMI within smart grids significantly enhances the capacity of energy management systems (EMS) to monitor, analyse, and report consumption or demand in near-real time. SMs constitute a pivotal element in enabling online EMS operations and are especially critical in the integration of EVs into the grid since these devices provide timely information on instantaneous demand and consumption. As recent literature highlights, smart-meter-based forecasting supports day-ahead and intraday planning, which is crucial to balancing generation and load in modern power systems [60]. In the context of EV integration, SMs serve as the interface through which dynamic and large loads are tracked and managed. The real-time data captured by SMs facilitate more accurate demand forecasting and enable dynamic pricing mechanisms, thereby improving the feasibility of demand-side management and pricing strategies. Indeed, forecasting tools relying on SM data have been shown to support the pivot from conventional billing and static rates towards more adaptive frameworks [44].

The AMI architecture encompasses a broad array of technologies and applications integrated into a cohesive operational framework. Typical components include meter data management systems (MDMS), home area networks (HANs), the smart SMs themselves, sensor networks, computer hardware and software, and communication technologies such as broadband over power line (BPL) or power line communication (PLC), as well as wireless links. These communication systems enable

two-way connectivity between utilities, SMs, sensors, and EV management systems (EVMS), thus facilitating real-time data exchange and control [61]. By leveraging AMI, utilities and aggregators can implement intelligent decision-making and control systems, such as scheduling EV charging under dynamic pricing schemes or peak-shifting strategies. In one concrete study, an EV-charging-AMI platform reduced peak energy consumption by approximately 36 % and increased off-peak energy demand by approximately 54 % [62]. These shifts not only alleviate stress on the distribution system during peak periods but also smooth the demand profile, enhancing system reliability and operational efficiency. Fig. 4 illustrates the AMI framework enabling EV-smart grid interaction, where SMs collect and transmit energy usage data via BPLC or WiMAX across HAN, LAN, or FAN networks to the AMI head-end system for validation and transfer to the MDMS. The MDMS manages, stores, and analyses this data, allowing utilities or aggregators to access energy information through consumer web portals that interface between the EVMS, MDMS, utility, and energy market.

Beyond charging only, AMI supports other V2G and V2H services by providing bidirectional measurement and communication capabilities. This enables EVs to serve as controllable loads or storage devices in the grid, further augmenting the flexibility and intelligence of the grid's operational paradigm. Consequently, AMI represents a foundational technology for enabling high-fidelity monitoring, real-time communication, and advanced load management in smart grids with substantial EV penetration [63].

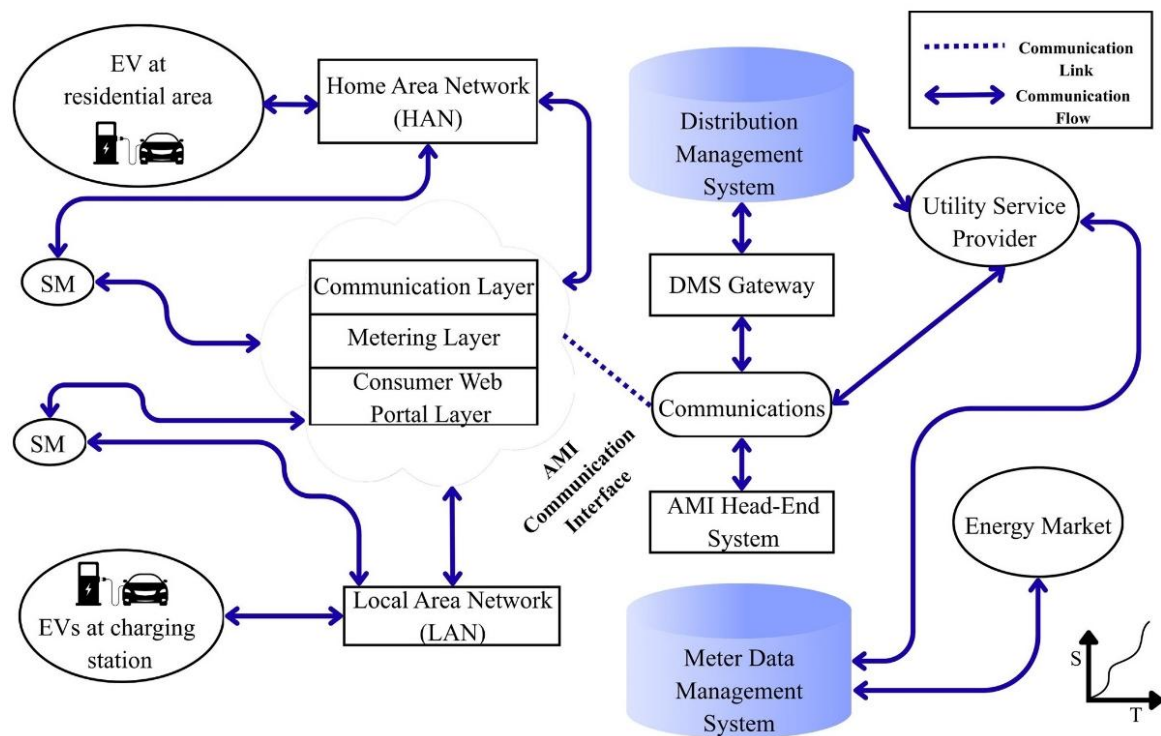


Fig. 4. Overview of the advanced metering infrastructure architecture within the V2G framework [61]

### 4.3. Advanced Communication and Control Network Infrastructure for EV

A two-way communication network within the smart grid infrastructure establishes the foundation for enabling demand response technologies that regulate DERs across geographically dispersed areas. Wireless communication has emerged as a key enabler for V2G applications because of its cost-effectiveness, scalability, and wide area coverage. In EV interactions with the smart grid, frequent bidirectional communication between SMs and other system components is required to ensure reliable operation. Communication in EV integration can be categorized into two levels: first, between advanced sensors or EVMS and SMs; and second, between SMs and GOS or aggregator data centers. The first scenario may utilize PLC or wireless solutions, whereas the latter generally relies on broadband mobile networks such as WiMAX, 4G LTE, or emerging 5G systems [28], [64].

However, the increasing penetration of EVs introduces challenges in monitoring, communication, and control architecture due to the vehicles' high mobility. A smart meter must therefore support seamless connectivity when an EV moves across networks operated by different aggregators or energy suppliers. As highlighted in [65], recent advancements in wireless communication significantly enhance the feasibility of smart metering and V2G services, particularly since EVs are geographically distributed. For successful operation, EVs must connect dynamically to available charging points to either draw power for battery recharging or inject power back to the grid. GOs or aggregators must identify specific EVs in near real time for billing and energy accounting, while EVs must receive time-of-use or real-time price signals from the energy market to optimize power exchange efficiency [66].

Wireless sensor networks (WSNs) are increasingly recognized as an essential technology in smart grid operations, particularly for distributed generation (DG) and MG management [67]. Extending this concept to EV systems can enhance data collection and control functionalities, though WSN adoption in V2G remains challenging due to limited communication range and higher packet delay when multiple hops are involved. Recent research in [68] proposed a WSN-based information architecture for V2G, improving grid demand profiling and reducing message broadcasts. Similarly, ZigBee has been explored for EV applications, offering simplicity and low bandwidth requirements. Nevertheless, communication interference, limited memory, and latency issues must be resolved to enhance reliability for large-scale V2G deployment [69]. The comparative characteristics of wireless communication technologies applicable to EV-based V2G systems are summarized in Table 3.

Cybersecurity also remains a critical aspect in EV-smart grid communication. Secure data transmission between EVs, aggregators, and the energy market is essential to prevent cyber threats such as data manipulation, price tampering, or system congestion caused by malware attacks. Unsecured communication can significantly undermine the reliability and economic benefits of V2G integration [74]. Ensuring secure authentication and data protection in visiting networks is equally vital. As depicted in Fig. 5, the selection of wireless technology depends on communication range, data rate, and network hierarchy. For instance, WiMAX supports long-range connectivity between aggregators, utilities, and energy markets, while near-field communication (NFC) can simplify local pairing between EVs and smart devices to enhance connection reliability [75].

**Table 3.** Comparison of wireless communication technologies for V2G integration

S/N	Technology	Operating frequency	Covered distance	V2G relevance
1	Bluetooth (BLE 5.2-5.4) [70]	2.4 GHz ISM band	10-100 m	<ul style="list-style-type: none"> <li>• Suitable for short-range authentication and diagnostics</li> <li>• BLE 5.x improves energy efficiency and connection reliability</li> </ul>
2	Zigbee (IEEE 802.15.4 / ZigBee PRO 2023) [71]	868 MHz (Europe) 915 MHz (North America) 2.4 GHz (Worldwide)	10-100 m	<ul style="list-style-type: none"> <li>• Ideal for smart home or building-level EV energy coordination</li> <li>• 2023 update enhances AES-128 security and low-power operation</li> <li>• Primary wide-area communication standard for V2G</li> </ul>
3	4G LTE / 5G NR / C-V2X [72]	Licensed sub-6 GHz & mm Wave bands	Urban 0.5–2 km Rural 10 km+	<ul style="list-style-type: none"> <li>• Enables <math>\leq 1</math> ms latency and network slicing for aggregator control</li> <li>• Successor to IEEE 802.11p for V2X and V2G applications</li> </ul>
4	IEEE 802.11bd (Next-Gen DSRC) [73]	5.9 GHz band / 60 GHz enhanced	500-1000 m	<ul style="list-style-type: none"> <li>• Offers 3-times higher throughput and <math>&lt; 10</math> ms latency</li> <li>• Suitable for secure EV authentication and payment</li> </ul>
5	Near Field Communication (NFC) [64]	13.56 MHz	5-10 cm	<ul style="list-style-type: none"> <li>• 2025 release extends range and supports passive power harvesting</li> </ul>

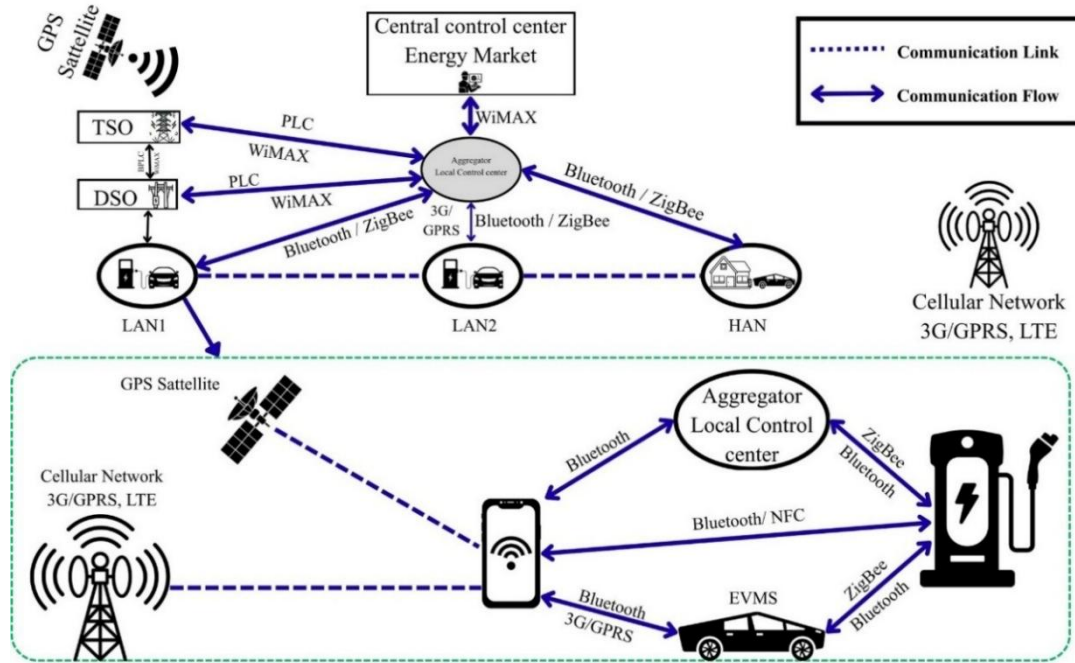


Fig. 5. Communication network architecture for EVs integrated with the smart grid [75]

## 5. Integration of Renewable Energy Sources with EV Systems

The large-scale integration of RES, notably wind and PV systems, is central to decarbonizing power systems, yet their inherent intermittency and non-dispatchability produce variable generation that can exceed or fall short of demand and thereby reduce effective capacity credit for system planners. Maintaining system balance under high-RES penetration therefore requires additional flexibility such as stationary ESS or controllable loads. However, the high capital cost of large-scale ESS constrains rapid deployment.

The electrification of transport offers an alternative flexibility resource by treating aggregated EVs as distributed storage. When coordinated, EV charging and bidirectional V2G operations can meaningfully support peak shaving and system cost reductions. Recent reviews and modelling studies report that V2G and managed EV participation can reduce peak grid demand by up to 20% and deliver system cost savings on the order of 10–15% in suitable scenarios [9], [65]. Controlled charging policies have also been shown to reduce charging-related emissions and curtailment of VRE; utility-controlled or emissions-aware charging strategies reduced emissions by about 7% relative to uncontrolled charging, while time-of-use and emissions-responsive charging schemes achieved 14.1% reductions in charging costs and 15.7% reductions in GHG emissions in demonstrated cases [76], [77]. Other studies indicate coordinated charging can simultaneously reduce peak power demand and CO<sub>2</sub> emissions by double-digit percentages (for example, CO<sub>2</sub> reductions of around 18% and peak reductions up to 33% in regional simulations), underscoring the sensitivity of results to assumptions about grid mix, EV penetration, and control algorithms [78].

Fig. 6 illustrates the conceptual integration of PV and wind generation with aggregated EVs at public or workplace charging stations. In this configuration, EVs act as distributed energy buffers: absorbing surplus RES generation through managed charging and supplying energy back to the grid via V2G when RES output is low. The schematic assumes the communications and control infrastructure necessary for real-time coordination between RES, EV aggregators, and grid transformers  $T_i$  (where  $i = 1, 2, \dots, n$ ) is available. Collectively, the cited evidence shows that evidence-based EV scheduling and V2G can improve renewable utilization and provide measurable operational and environmental benefits without relying solely on high-cost stationary storage [45], [63].

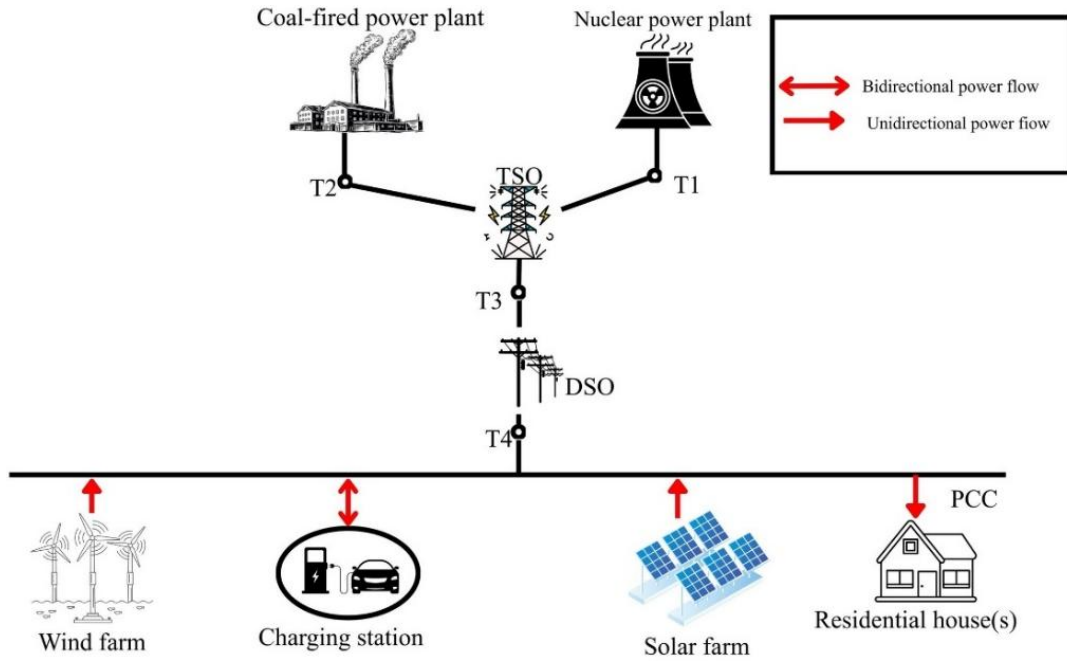


Fig. 6. Integration of wind and photovoltaic energy sources into the electric grid with EVs [63]

### 5.1. Integration of Photovoltaic Solar Energy with EVs

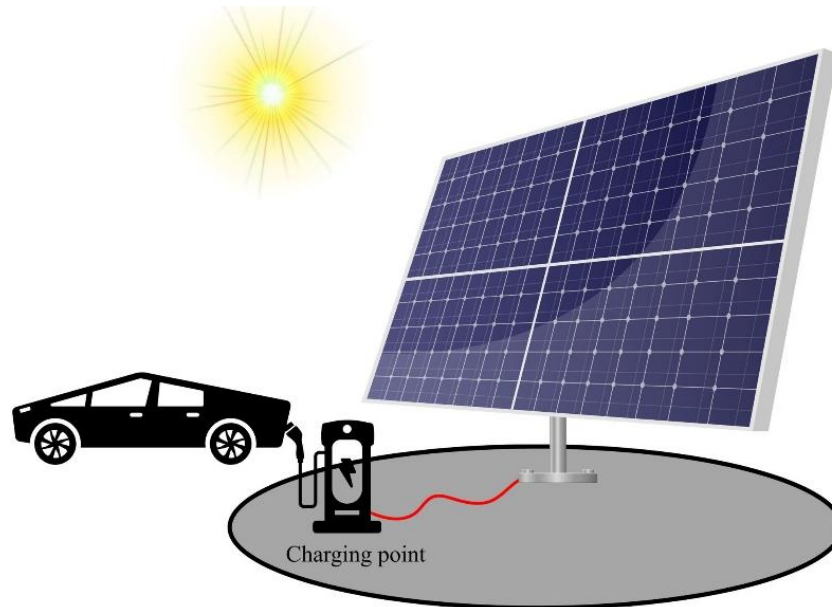
PV solar energy has emerged as a viable and sustainable option for supplying electric EV charging and supporting grid stability. Integrating PV generation with EV infrastructure enables localized renewable utilization, minimizes distribution losses, and reduces the dependency on central grid generation. The deployment of PV arrays on rooftops and solar carports at parking facilities is particularly attractive for workplace and commercial environments where daytime vehicle dwell times align with solar availability. Recent analyses have reported that PV installations on parking infrastructure could supply approximately 15–40 % of projected EV charging demand in dense urban areas, depending on solar potential, vehicle occupancy patterns, and parking durations [79].

At mid-latitude regions where average daily solar irradiance ranges between 3.0–3.5 kWh/m<sup>2</sup>, medium-scale carport systems with capacities around 80–120 kW can effectively sustain multiple EV chargers while maintaining favourable payback periods. A techno-economic study demonstrated that a 115.8 kW PV carport could reliably power a workplace charging hub, significantly reducing electricity purchases during daylight hours [80], [81]. Smaller pilot projects have validated these findings experimentally; for instance, a 4.89 kWp PV carport installation achieved monthly energy production of approximately 470.75 kWh, confirming the practicality of such systems for aggregated EV charging operations [79], [82].

The incorporation of bidirectional V2G operation enhances the synergy between PV generation and EVs. Aggregated EV batteries can absorb excess PV energy during peak generation periods and discharge back to the grid or local load during low-irradiance intervals. Coordinated scheduling frameworks have been shown to increase PV utilization by 10–20 % and reduce daily operational costs by up to 12 %, depending on the applied charging optimization strategy [83]–[85]. These benefits are further amplified when EVs participate in frequency regulation and ramp-rate control, mitigating short-term solar output variability. Fig. 7 illustrates a standalone PV carport charging station at a workplace or public facility. In this system, multiple EVs are connected through bidirectional DC/AC converters governed by an energy management controller that schedules charging and discharging according to real-time solar generation and grid conditions. The design minimizes power conversion stages and improves local self-consumption of solar energy.

Expanding this concept, Fig. 8 depicts a grid-connected PV-EV infrastructure comprising multiple charging stations interfaced through bidirectional power converters. Stations 1 and 2

demonstrate a distributed configuration where aggregated EVs can collectively act as energy storage units, supporting grid voltage stability and peak-load reduction through coordinated V2G operation. The DC-linked architecture offers advantages such as reduced conversion losses, simplified power flow control, and flexible integration of PV generation, energy storage, and EV subsystems [86]. Such hybrid AC/DC topologies are increasingly viewed as promising designs for next-generation EV-integrated renewable networks.



**Fig. 7.** EV charging station powered by standalone photovoltaic rooftop installation at a parking lot [79]

Comprehensive studies also underline the importance of optimal scheduling algorithms and predictive energy management in maximizing economic and environmental outcomes. Dynamic optimization techniques such as model predictive control or metaheuristic algorithms have successfully minimized operational costs in PV-based industrial MGs with integrated plug-in EVs [87]. These methods ensure that the variability of solar power is efficiently compensated while maintaining grid stability and minimizing communication overhead.

Overall, the integration of PV solar energy with EV charging infrastructure demonstrates strong technical feasibility and environmental value. When appropriately sized and managed, PV-EV systems can contribute substantially to emission reductions, load balancing, and renewable energy utilization in urban and MG contexts. Future research directions emphasize lifecycle cost analysis, degradation modelling of EV batteries under V2G operation, and scalable communication architectures for real-time coordination.

## 5.2. Integration of Wind Energy Systems with EVs

The deployment of wind energy conversion systems (WECSs) is now widely regarded as a cost-effective and mature renewable generation option. Parallel to this trend, the aggregation and control of EVs via V2G and smart-charging schemes have been increasingly studied as a flexibility resource for power systems [87]. Recent research conclude that coordinated EV operation can materially increase usable wind penetration and reduce curtailment by providing frequency regulation and other ancillary services while acting as distributed storage [88]. These reviews in [44], [63], [65] combine insights from both modelling and field-scale studies, emphasize that the degree of benefit depends strongly on EV availability, user participation rates and the market or control arrangements that remunerate or direct EV flexibility.

Recent empirical and modelling studies provide clear evidence of the strong interaction between wind energy systems and EVs. A scheduling study conducted in mountainous power grids showed that when the proportion of EV users responding to grid scheduling increased from 30% to 60% and

then to 100%, wind power utilization improved significantly from 72.1% to 81.04% and 92.69%, respectively. This result highlights how user participation has a major influence on how much wind energy is actually consumed locally rather than curtailed [88]. Other studies and reviews also confirm that V2G-enabled EV fleets can reduce wind power curtailment and enhance system flexibility, especially in power systems with high renewable energy penetration [89], [90]. The overall reliability of the system improves further when EV aggregation is supported by effective market mechanisms or control incentives [91].

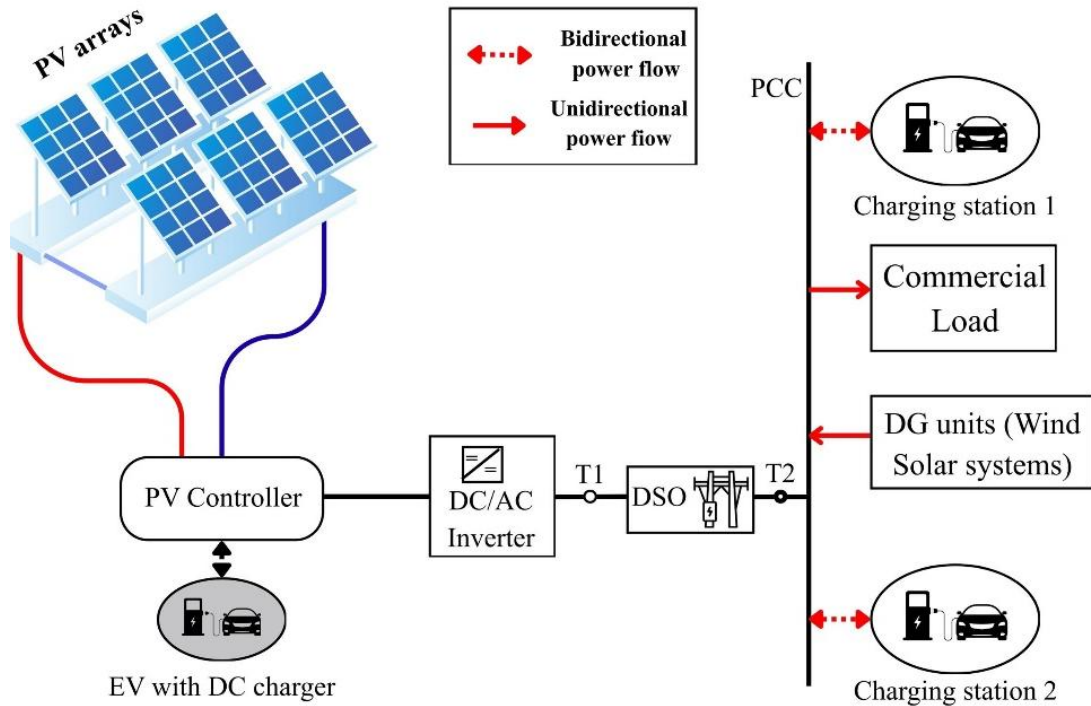


Fig. 8. Grid-connected photovoltaic solar system powering an EV charging station at a parking lot [81]

In MGs and VPP applications, coordinated scheduling of wind generation with EV charging and discharging helps balance variable power generation and demand. Studies show that on large-scale EV grid integration (EVGI) reveal that inverter control strategies play a vital role in maintaining grid stability. Implementing vector control in the  $dq$  reference frame enables EVs to provide ancillary services such as frequency regulation, reactive power support, and harmonic mitigation [92]. These findings indicate that realistic EV fleet behaviour, including charging and discharging patterns, must be incorporated into modelling to accurately evaluate the technical and operational benefits of combining wind energy systems with EVs, particularly in islanded or weak grids.

Overall, the recent literature shows that integrating WECSs with smartly managed EV fleets through advanced charging and V2G control is a practical and effective way to increase wind energy use and improve short-term grid stability [93]. However, real-world implementation still requires attention to several factors, such as driver behaviour, battery state-of-charge limits, degradation effects, and suitable market and regulatory frameworks to ensure reliable, safe, and cost-effective operation [92].

## 6. Feasibility and Challenges of Smart V2G Integration

The integration of EVs with the power grid has attracted growing attention from academia, industry, and research institutions. Various studies have investigated applications of EVs within the smart grid, highlighting their potential to provide services such as frequency regulation, peak shaving, and demand response [65]. Despite this, practical implementations of V2G systems remain limited. Critical enabling technologies including advanced batteries, communication protocols, and

bidirectional power interfaces are still under development [9]. Additional research and innovation are needed to improve system efficiency and reduce costs, particularly for EV charging infrastructure. Early pilot projects have demonstrated the technical feasibility of V2G, showing that EVs can supply real-time frequency regulation [94]. However, these demonstrations often involved a single vehicle, making it difficult to generalize findings to large EV fleets, where coordination, scalability, and operational complexity present additional challenges.

### 6.1. Intelligent EV Scheduling and Grid Integration

The rapid proliferation of EVs has introduced new challenges to power systems, particularly concerning the increased and highly variable load demand during charging periods. If left uncoordinated, simultaneous charging of a large EV fleet can induce significant peak loads, voltage deviations, and network congestion. Therefore, intelligently coordinated EV scheduling has become essential to ensure reliable operation and efficient utilization of grid assets. Intelligent scheduling distributes charging loads temporally and spatially across the network while respecting system constraints and user requirements. This coordination requires advanced communication, data exchange, and control infrastructures across multiple stakeholders, including GOs, aggregators, and EVMS [95], [96].

Recent advancements in smart grid technologies, supported by digital communication, vehicle connectivity, and real time metering, have enabled the large-scale deployment of smart charging strategies. These systems leverage two-way communication between EVs and grid control centers to dynamically manage charging behaviour according to grid conditions and electricity prices. Modern EVs and charging stations are increasingly equipped with wireless connectivity, GPS, and Internet of Things (IoT) interfaces that facilitate vehicle to infrastructure (V2I) and V2G interactions. This technological convergence allows for adaptive scheduling that integrates real time grid data, renewable generation forecasts, and user preferences to optimize charging profiles [64], [97].

To demonstrate the technical and economic feasibility of such systems, several pilot projects have been launched globally. In Taiwan, the 2023 collaboration between Gogoro and Enel X represents a landmark integration of battery swapping networks into a VPP. The project connects over 2,500 GoStations across 1,000 locations, dynamically coordinating their charging and standby cycles to provide grid balancing and demand response services [98]. Although primarily an industry deployment, this initiative exemplifies the operational potential of aggregating distributed EV infrastructure as dispatchable grid resources.

In China, NIO and CATL have pursued large scale deployment of passenger vehicle battery swapping networks. Peer reviewed studies indicate that NIO's business model and nationwide expansion strategy demonstrate high service reliability and strong user acceptance while reducing downtime compared to conventional fast charging [99], [100]. The company's integration of standardized modular batteries has also enhanced interoperability and scalability, key factors identified by recent policy and economic analyses on battery swapping services.

Complementary to swapping based systems, smart charging and V2G pilots in Europe and Asia such as Enel X's Project Flow and Mercedes Benz's smart fleet initiatives have validated the technical feasibility of coordinated EV scheduling for grid services [101], [102]. These projects combine intelligent meters, GPRS communication, and secure cloud-based data management to implement real time control and dynamic price signalling. Studies confirm that such coordinated frameworks can provide frequency regulation, peak shaving, and voltage support without significant impacts on battery health or user satisfaction.

Collectively, Collectively, recent demonstrations and academic studies show that intelligent EV scheduling is becoming a practical solution for integrating a high number of EVs into modern power grids. This approach includes both smart charging and battery swapping methods. Its successful implementation depends on reliable communication systems, flexible control algorithms, and supportive regulatory policies. Recent research also indicates that combining intelligent scheduling

with VPP platforms and dynamic pricing can improve grid flexibility and economic efficiency. These advancements support the ongoing transition toward sustainable and fully electrified transportation.

## 6.2. Renewable Energy Integration Enabled by EVs

The integration of RES, particularly PV and wind energy, with EVs has emerged as a key enabler for sustainable grid transformation. EVs can serve as distributed ESS that facilitate higher renewable penetration by mitigating intermittency and enhancing grid stability. Coordinated charging and discharging of EV fleets improve load balancing, voltage regulation, and overall renewable utilization efficiency [18], [44].

A notable example of this concept is the Realising Electric Vehicle to Grid Services (REVS) project implemented in Canberra, Australia. The initiative deployed 51 Nissan Leaf vehicles equipped with bidirectional chargers to assess their capability to provide grid services such as frequency regulation, peak shaving, and renewable energy smoothing [103], [104]. The project demonstrated that aggregated EVs can absorb excess energy from renewable sources during off-peak hours and inject it back into the grid when demand increases, thereby supporting both operational flexibility and energy decarbonization. Fig. 9 illustrates one of the REVS demonstrations charging sites, depicting the bidirectional charging infrastructure and communication enabled control system used for renewable integration.

Other international demonstrations have further validated the potential of EV based renewable integration. The Zem2All e-mobility pilot project in Málaga, Spain, involved 200 EVs and 229 charging points, including 29 CHAdeMO DC fast chargers, six of which offered bidirectional V2G operation. The project revealed how EV fleets can effectively balance variable renewable generation in urban grids [105]. Likewise, the V4Grid project in Central Europe, funded under the Interreg program, investigates Vehicle to everything (V2X) applications including V2G and Vehicle to home (V2H) to enhance renewable energy flexibility across multiple regions [106].

Collectively, these demonstration programs underscore the growing role of EVs as DERs that strengthen renewable energy integration. The synergy between EVs and RES contributes to improved grid reliability, reduced operational costs, and enhanced energy sustainability through intelligent scheduling and bidirectional power exchange. Continued development of advanced charging protocols, adaptive control algorithms, and supportive regulatory frameworks remains vital for achieving large scale renewable EV integration.



**Fig. 9.** V2G charging technology launched at realising electric vehicles services (REVS) in ACT through Nissan Leaf vehicles at Canberra, Australia [103]

### 6.3. Assessment of V2G Benefits, Constraints, and Future Prospects

In V2G systems, EVs function as dynamic DERs capable of providing ancillary services such as frequency regulation, voltage stabilization, and peak demand reduction. Recent research demonstrates that V2G enhances grid flexibility and facilitates renewable energy integration while providing potential financial incentives for EV owners [75], [107]. Compared to conventional storage systems, V2G leverages the existing EV charging infrastructure, reducing the need for additional investment in dedicated storage facilities. Although large-scale technologies such as pumped hydro storage, flywheels, and concentrating solar power (CSP) remain the primary grid-balancing methods, the distributed and flexible nature of V2G makes it an attractive complement to centralized energy storage [108].

The practical deployment of V2G faces significant technical and operational challenges. Bidirectional chargers, standardized communication protocols, and secure data interfaces are essential for large-scale implementation. Many commercially available EVs still operate with UC chargers, and only a limited number of models currently support full V2G operation via CHAdeMO or ISO 15118-20 standards [109]. Another critical factor is battery aging, as frequent charge–discharge cycling can accelerate degradation.

To achieve reliable large-scale V2G integration, several key barriers must be addressed. Battery degradation, market limitations, and lack of standardization in communication protocols, charging interfaces, and grid codes constrain system performance and scalability. Unidirectional smart charging minimizes battery wear and implementation costs but offers limited grid support, whereas bidirectional V2G enhances flexibility and ancillary services at the expense of greater system complexity and battery stress. Aggregator- and VPP-based approaches improve coordination and scalability but depend on advanced ICT infrastructure and accurate forecasting. Addressing these technical, economic, and regulatory challenges through integrated strategies is essential to enable cost-effective, reliable, and large-scale V2G deployment. Empirical studies between 2021 and 2024 have reported that regular V2G participation can increase total battery wear by approximately 9–14% over a ten-year period, depending on usage intensity, depth of discharge, and temperature conditions [75], [110]. Thus, while technically feasible, widespread V2G adoption requires battery management strategies and compensation mechanisms to mitigate long-term impacts on battery life.

From an economic standpoint, the profitability of V2G depends heavily on local electricity market structures and tariff designs. Research indicates that the highest economic benefits are achieved in deregulated markets with significant peak-to-valley price variations and established demand response frameworks [63], [80]. In contrast, in regulated or flat-rate systems, operational costs and degradation-related expenses often outweigh the financial gains. Pilot projects in Europe and Australia have shown modest user revenues, averaging around USD 8–10 per month (approximately USD 100 per year) under real-world operating conditions [111], [112]. Despite these limitations, the strategic value of V2G extends beyond direct revenue generation. When aggregated within VPP frameworks, EV fleets can enhance renewable energy utilization, improve grid stability, and support MG resilience. Continued research and policy coordination are therefore crucial to establish standardized regulations, interoperability frameworks, and business models that enable the full realization of V2G's long-term potential [38], [46], [107].

## 7. Conclusion

This paper has provided a comprehensive review of the interaction between EVs and modern smart grid infrastructures, emphasizing their role in enabling a more sustainable and resilient energy ecosystem. The integration of RES through EVs has been critically discussed, highlighting their potential to deliver ancillary services such as frequency and voltage regulation, peak shaving, and reactive power support. These capabilities enhance grid stability, improve operational efficiency, and reduce overall system operating costs. The findings underscore that successful large-scale deployment of EVs within smart grid frameworks depends on advancements in communication networks,

intelligent control algorithms, and precise metering technologies, all of which facilitate interoperability and real-time coordination between EVs and the grid. Furthermore, the feasibility of V2G implementation has been examined in recent pilot projects and demonstration studies. Despite growing interest, limited penetration of V2G enabled EVs continues to constrain market adoption. Automotive manufacturers face challenges in balancing the additional costs associated with bidirectional power converters against consumer demand and long-term profitability. From a technical standpoint, battery degradation under frequent charge and discharge cycling remains a major barrier to widespread V2G participation. Future research should prioritize longitudinal experimental studies that evaluate lithium-ion battery cycle life under realistic V2G frequency regulation and ancillary service dispatch patterns, incorporating variations in depth of discharge, charging power, and thermal conditions. While LFP batteries have shown promising durability, further investigations are required to develop robust strategies for extending battery lifespan, improving thermal stability, and conducting comprehensive cost–benefit analyses for V2G operations. Similar studies on other chemistries, such as nickel metal hydride and alternative lithium-ion variants, are essential to identify optimal technologies for future grid interactive EV applications.

Finally, it is important to acknowledge that dynamic grid phenomena, such as voltage dips and frequency deviations, pose inherent challenges to reliable V2G operation, particularly in weak or islanded networks. Policy and market interventions, including targeted incentives, demand response programs, and regulatory frameworks, could encourage V2G participation while ensuring economic viability for both utilities and consumers. Research addressing these aspects, combined with modelling and experimental validation, will be critical for secure, efficient, and large-scale deployment of V2G technology in future smart grids. The integration of intermittent renewable sources like solar and wind energy via coordinated EV operation presents additional complexity that must be thoroughly investigated through both modelling and experimental validation. A comprehensive understanding of power system dynamics, coupled with advancements in adaptive control, communication resilience, and cybersecurity, will be fundamental to achieving secure, efficient, and large-scale deployment of V2G technology in future smart grids.

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