



Article Electric Vehicle-to-Grid (V2G) Technologies: Impact on the Power Grid and Battery

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Abstract: The gradual shift towards cleaner and green energy sources requires the application of electric vehicles (EVs) as the mainstream transportation platform. The application of vehicle-to-grid (V2G) shows promise in optimizing the power demand, shaping the load variation, and increasing the sustainability of smart grids. However, no comprehensive paper has been compiled regarding the of operation of V2G and types, current ratings and types of EV in sells market, policies relevant to V2G and business model, and the implementation difficulties and current procedures used to cope with problems. This work better represents the current challenges and prospects in V2G implementation worldwide and highlights the research gap across the V2G domain. The research starts with the opportunities of V2G and required policies and business models adopted in recent years, followed by an overview of the V2G technology; then, the challenges associated with V2G on the power grid and vehicle batteries; and finally, their possible solutions. This investigation highlighted a few significant challenges, which involve a lack of a concrete V2G business model, lack of stakeholders and government incentives, the excessive burden on EV batteries during V2G, the deficiency of proper bidirectional battery charger units and standards and test beds, the injection of harmonics voltage and current to the power grid, and the possibility of uneconomical and unscheduled V2G practices. Recent research and international agency reports are revised to provide possible solutions to these bottlenecks and, in places, the requirements for additional research. The promise of V2G could be colossal, but the scheme first requires tremendous collaboration, funding, and technology maturation.

Keywords: electric vehicles; energy; vehicle-to-grid (V2G); battery; life cycle

1. Introduction

In this last decade, the use of sustainable green energy sources has been welcomed globally with much stricter enforcement of carbon taxes to abate global climate change [1]. In 2016, the Paris Agreement enforced the rule to circumvent global temperature rise below 2 °C. According to the report from the international renewable energy agency (IRENA), the renewable energy shared from green sources, especially from the solar power plants, are on the rise (Figure 1) [2]. Green energy production across Asia has sharply increased over the last decade, with an improvement of more than 150,000 MW of installed capacity from 2020 to 2021 (Figure 2) [3]. The global roadmap of IRENA showed that by 2050, more than two-thirds of energy production would be from renewables, increasing clean electricity consumption from 20% to 40% [4]. Moreover, renewable generation from wind and solar



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can show a triple contribution from 20% to 60% by 2050. On another front, policies have been dispatched to efficiently check fossil-based vehicles' large growth.

Figure 1. Trends in renewable energy generation in GW [2].



Figure 2. Trends in renewable energy capacity by region in MW [3].

In the transportation sector, the replacement of internal combustion engines (ICE) with electrical vehicles (EV) has shown promise over the last decade in curtailing overall greenhouse gas (GHG) emissions. The international energy agency (IEA) in 2022 highlighted that the global stocks of EVs have increased with the drastic increase in public awareness of EV use and the reduction in running costs from 2015–2021 [5]. Among other types, from 2018 to 2020, the worldwide stock of light-duty passenger EVs doubled from 5.1 million to 10.2 million (Figure 3). In 2018 alone, the EVs crossed 5 million in headcount, a ~63% increase from the number of EV cars in 2017. China, Europe, and the US contributed 45%, 24%, and 22%, respectively [6].



Figure 3. Trends in global electric vehicle stocks [5].

The electrification of conventional vehicles requires sufficient charging stations and long-lasting batteries with high charge density to back the EV for longer travel distances and better propulsion [7]. In recent times, the government and industrial entities have come forward with innovative regulatory policies and incentives to bolster necessary research and experiments to lower the EV unit cost and improve user convenience with EV charging and maintenance [8]. Tesla claimed to hit a 300 miles/run target from a newly formed Lithium-ion battery. Samsung has produced an EV vehicle battery that takes 20 min charge to drive for a 375-mile travel range. The US department of energy has taken the initiative and incentives for establishing charging infrastructure nearest to the EV parking stations to improve user experience.

The use of EVs could be more economical, with a lower CO_2 footprint than traditional ICEs. For the ICEs, the fuel conversion efficiency usually lies below 30%, making the overall efficiency lower than 60%. EVs' electricity-to-mechanical power conversion efficiency could reach near 77%, contributing to overall 85–90% vehicle efficiency [9]. Plug-in EVs (PEVs) and plug-in hybrid EVs (PHEVs) improve fuel economy and reduce fuel cost, and compared to traditional ICE, EV emits lower GHGs. The GHGs footprint from EVs is ~40% lower than the ICE. In 2018 alone, 78 Mt CO2-eq of emission resulted from ICE compared to 38 Mt CO2-eq for EVs. The amount of CO_2 reduction by the EV largely depends on the energy sources and EV charging pattern [10]. The required electrical power for EV charging could be drastic. In 2018, the global electric fleet consumed more than 55 TWh of electrical energy. The EVs in China alone comprise 80% of the total EV electrical energy consumption. Moreover, China contains 44% of the worldwide EV manufacturing farms, followed by Europe with 24% and the USA with 22%. Thus, many manufacturing farms in the local market play a vital role in EV-related electrical energy demand.

It is estimated that the total emission from the ICEs would show an annual 1.9% drop till 2040. However, by 2040, the vast adaptation of EVs might have a more dominant role in the EV market growth and culture. The global presence of EVs was estimated in 2018 to cross 130 million units by 2030; as of 2021, the EV population has surpassed the 12 million range [11]. However, the drastic rise in EV adoption would warrant an immense burden on the traditionally built power grids, which were not designed to carry the sporadic enormous demands from the random charging of EV fleets. Moreover, the electrical components, such as power transformers and generator units, would become very vulnerable to the change in system frequency when great demand from EVs is inserted or discarded rapidly to or from the power grid [12]. Thus, the power system's maturation is essential to uphold vast EV growth. In this regard, many government incentives are required to bear the high cost of upgrading or replacing the existing power infrastructure. The great demand for EVs could be addressed by distributing and placing generating units alongside the large EV charging infrastructure and with proper EV scheduling. The battery and power electronics stages are now being explicitly considered to extract the power stored within the onboard battery units of the EVs. The DC energy would then be inverted and fed to the power grid in times of greater demand than the generation limits, implementing the vehicle-to-grid (V2G) scheme. Controlled V2G scheduling could shave peak load demand, make room for renewables integration, and reduce charging costs.

The EVs can be used for electrical loads at the charging points and the distributed battery energy storage systems (BESS) for peak load demand compensation. Additional storage elements incorporated into the grid can enhance spinning reserve and frequency regulation and benefit from the grid operation by selling power during peak hours. The battery's discharge cycle has improved significantly over the last decade, boosting the feasibility of the V2G technique to marketize. In a scenario of bi-direction power flow between load, EVs, and power grids, the efficacy of the perfect synchronization and minimization of loss is achieved by establishing communication and control links across each entity.

Two important elements of establishing V2G, the power flow control and reading of the energy metering infrastructure (EMI), are mainly directed by centralized or decentralized control [13]. A win-win marketing scenario between the power grids and the EVs maximum utilization of the V2G technique should be carried on. In the centralized technique, the grid incentives and profit are considered the core insight of operation by extending or curtailing the embedded EV fleets. The charging or discharging of EVs depends mainly on improving the operating efficiency of the power grids. In a decentralized control scheme, definite procedures are dispatched to maintain the charging/discharging pattern of the EVs while maintaining the proper operation of the grid. Implementing and commensurating perfect relations between EV users and grid operators requires decreasing power generating costs, power loss, and variable loads while increasing the diversity factor of the power system [14].

In the current literature, researchers focus on mathematical modeling, optimization techniques, and algorithms to incorporate EV systems into the power grid in an efficient manner. Moreover, utilizing distributed renewable generation sources such as PV and wind for charging EV batteries is also a hot topic. Investigation of battery energy storage devices and their life cycle analysis, the impact of EVs on the environment, and load scheduling are also under consideration. However, the impact of EVs on futuristic grids such as smart grids or microgrids is still lacking. Furthermore, apart from a large book chapter, no single research article has lucidly demonstrated the current V2G trends, challenges in battery and grid parameters, economical business models, types of EVs on the run, and research gaps across these domains. Since V2G technology could become more ubiquitous in the coming years, it is necessary to investigate the impact of EVs and V2G technology on power quality, battery cycle, waste management, and many more areas. Herein, a well-structured and in-depth investigation of V2G technique implementation challenges, possible solutions, current V2G practices across industry and academia, business models, and research gaps are highlighted. This article contributes to the following points:

- Detailed revision of V2G system, types, and architecture.
- Overview of the current and future V2G industrial outlook and business models.
- The prospects of V2G for futuristic smart grid and distributed generation.
- Challenges associated with the V2G application on both grid and vehicle sides.
- Highlighting the recent research works and policies to address the challenges with V2G.
- Outlining the research gaps associated with each of the challenges and their present solutions in the literature.
- Power quality and harmonics profile investigation of the V2G technology.

The paper is designed as follows. Section 2 provides the prospects of the V2G system and V2G policies and business models. Section 3 provides background information on

EVs, V2G technologies, and the impact of V2G on power grids. Section 4 details the key challenges of implementing the V2G scheme. Section 5 provides the possible solutions for the challenges associated with effective V2G implementation by revising recent literature. Finally, in Section 6, we conclude the paper.

2. Prospects of the V2G System

2.1. V2G Present Scenario and Growth

In 2018, China, the United States, and the Nordic region (Denmark, Finland, Iceland, Norway, and Sweden) contributed to the top three EV markets. The per capita diffusion of EVs across the Nordic region hit nearly 11% and around 40% market share on the front of new EV sales. In 2020, the clean energy ministerial (CEM) initiated the EV30@30 campaign, which targeted reaching the global EV share to 30% of the automobile market [15]. By 2030, it is estimated that a colossal number (~245 million) of EVs, around 30 times the present count, can be on the road. By 2040, EV sales can hit nearly 1.5 billion [16]. Table 1 presents the trends in EV adoption across the globe in 2019–2021 [17]. The V2G culture is becoming more and more attractive as days pass due to an increased level of innovation from all fronts of supply lines, involving battery storage, advanced switching semiconductor-based power electronics, high functional field programming gate arrays, adaptive control strategies, and even from the data science point. A comprehensive survey study concluded that the income of the users is the primary factor that tunes EV ownership and garners public interest in participating in advanced features of EVs, such as V2G technology [18]. The amount of EV planning to consider V2G service is on the uptake. It was estimated in 2016 that more than 50 million newer users could participate in the V2G scheme from 2016 to 2030.

Roughly ~90% of the power plants run hours to meet the base load of power operation, and only 15–25% generation capacity improvement is required to match the peak power demand. Considering the major EV host countries, such as China, the United States, European Union, and India, the peak demand can be around 600 GW by 2030. The total EV fleet deployed across these regions can host onboard batteries lumped to 16,000 GWh [19]. Current research estimates only 60-80% of the nominal EV battery utilization capacity could be attained. It is observed that nearly 10% (20%) of the total energy coming from the EV batteries, using a 3 kW (8 kW) charger, is lost in the dc to ac power inversion process. Considering the worst-case scenario, with 60% utilization of battery capacity and 20% loss in the inversion process, the available power to the grid from the batteries across the abovementioned regions lumps to 7680 GWh, enough to meet the peak demands with a 1500 GWh surplus. Therefore, the projected power shared from the EV batteries would exceed the capacity of additionally erected peak power plant infrastructure by 2030. According to Figure 4 (shown in red), the ultimate technically feasible electricity contribution from the available EV fleet battery storage can rise roughly by 2000 GW annually until 2030. Figure 5 represents the expected growth of EV car stocks from 2020 to 2030 [20]. According to the projection, the number of BEVs and PHEVs would be roughly double every five years till 2030. In reaching the Sustainable Development Scenario-2030, the would-be available capacity from the EVs for V2G is provided in Figure 6 [21]. The figure provides the total generation capacity required for the project load demand and breaks it into the possible contribution from the V2G potential, distributed variable renewables, and other generation capacities.



Figure 4. V2G potential and variable renewable capacity relative to total capacity generation requirements in the Sustainable Development Scenario, 2030 [19].



Figure 5. Global EV sales from 2020–2030 [20].



Figure 6. Vehicle-to-grid potential in the Sustainable Development Scenario, 2030 [21].

Country	China	ina USA —				Eur	ope				Korea	Iapan	New	0 1
Country	China	USA	Germany	UK	Norway	Iceland	Sweden	Netherlands	France	Switzerland	Korea	Japan	Zealand	Canada
increase in electric car stock in 2020	4.5 million	1.7 million				3.2 m	illion					0.7	⁷ million	
electric car stock share of BEVs	80% (0.96 million)	78% (230,100)	-	62% (109,120)	73% (56,210)	-	-	82% (59,040)	60% (111,000)	-		0.4	l million	
increase in electric car stock share in 2021	46%	-				32	2%				-	-	-	-
new electric cars registered	1.2 million	295,000	395,000	176,000	77,000	-	28,000	72,000	185,000	-	31,000	29,000	-	51,000
electric car market share in 2021	30.00%	15.00%	-	8%	<1%	-	3%	30.00%	15.00%	-	8%	<1%	-	3%
electric car vehicle sales share	6%	~2%	~14%	~12%	75%	50%	32%	25%	~12%	_	2.90%	0.60%	-22%	0%

2.2. V2G Industrial Outlook for Investors and Policymakers

The EV market has been growing sharply in the last decade. From 2010 to 2020, the global EV cars' stock share improved by 0.9%. Figure 7 represents the growth of global EV stocks from 2010 to 2021 [23]. The amount of EVs on the run till 2020 has already provided 2854 million litres of gasoline-equivalent service [20]. The biggest hurdle is the lack of technical maturity to adequately provide and schedule the V2G technique [24]. The only widely used standard for the V2G technique is the Japanese CHAdeMO, which offers bidirectional power flow capabilities. However, till 2019, the diffusion of the CHAdeMO standard was limited across Japan, China, North America, and Nordic markets. Manufacturers from Nissan, Mitsubishi, and Renault are the top runners in the V2G front, dispatching nearly 50% of all field V2G projects. Other EV standards must be revised and upgraded to support efficient bidirectional power transfer between the battery and the grid.



Figure 7. Global electric car stock, 2010–2021, in thousands [23].

Another major hurdle to a successful V2G business model is the lack of structured regulatory frameworks to standardize V2G practices across borders. Many researchers and the automobile industry's research and development (R&D) section have come forward with suggestions and analyses. The business model requires a structured V2G infrastructure for the entire supply chain, as presented in Figure 8, which usually comprises three primary entities; the power grid utility, vehicle manufacturing company, and EV consumers [1]. In collaboration with Rolls-Royce, BMW has recently initiated a business plan for V2G implementation, shown in Figure 9 [25]. According to the model, the grid utility arranges funds, dictates the program schedule, and provides customer offers. The manufacturing company receives these data from the utility and acknowledges a fixed fee tariff rate. After that, required IT infrastructures for V2G power flow are initiated, focusing on an excellent customer experience and required charging control strategies. Finally, the user acknowledges the incentive payment plans set by the grid utility and opts-in to the power exchange through intelligent charging.

In 2021, IEA summarized all the key policies and measures released by governments across the globe between 2014 to 2020 related to zero-emission vehicles and EVs [26]. The outlined policies and measures are directly associated with the EVs and EV deployment roadmaps, and are generally composed of four primary classes: legislation—regulations and standards; targets—commitments and agreements; ambitions—goals and objectives; and proposals—public releases and parliament authorization [26]. The four classes interdepend on each other and complete the circle of innovating and improving current standards to meet targeted commitments (such as PA), initiating marketable and profitable business

policies and models, proposing the developed hierarchy of improvement to government bodies or the general public for further scrutinizing, and repeating the cycle.



Figure 8. Stakeholder and actor integration to policy measures in the vehicle-to-grid technology supply chain [1].



Figure 9. Vehicle-to-grid current business model initiated by BMW [25].

Investors and vehicle companies worldwide have realized the potential of V2G technology. By July 2019, more than 50 V2G projects were modeled to elect a suitable business model that has proper business prospects and makes the manufacturer, stakeholders, and charging developers profitable. Individual countries also started to showcase their technical competency to reach the V2G market faster than others. For instance, the Germany-based E. ON power utility company is developing a V2G business model with Nissan cars and renewable-based distributed generations. The automobile company Volkswagen has recently projected that by 2025 their EV fleet can generate nearly 350 GWh of energy backup. In September 2019, in the UK, Nissan and Électricité de France (EDF) initiated V2G technology development to serve the UK, France, Belgium, and Italy. In addition, in the same year, EDF dispatched a joint venture called 'Dreev' with California-based USA company Nuvve, which may focus solely on V2G technology development. Companies like Greenlots and Kinsensum focus on the software front to easily manage and communicate with the EV charger and control the grid services. V2G practices, technology development, and business model justification activities are primarily led by Nuvve, eMotorWerks, Plugshare, Greenlots, and Kisensum manufacturing companies across the globe. The requirement of standardized V2G implementation worldwide could be subsidized by following the standards already deployed in Japan. However, this calls for significant reform of the standards currently dispersed worldwide in the EV charger design and battery-backs allocation. The V2G certainly needs more time and contribution from investors, stakeholders, and major government incentives to become a structured and profitable business model.

2.3. Electric Mobility-Driven Socio-Environmental Vulnerabilities

Though the prospect of vast deployment of EVs and implementation of V2G technology seems a feasible solution to tune grid load demand and pave extra revenue earnings for the consumers, some inherent socio-economic and environmental issues must be considered.

First, in a report generated across the Nordic region (Denmark, Finland, Iceland, Norway, and Sweden) from nearly 260 experts in the field, it is concluded that EV and V2G practices are primarily viable for the rich and higher economic class–people who can afford an EV unit [27]. The externalities may lead to hacking, cyber-attacks, and privacy breaches of the people who enjoy the V2G practices by those who blend in the marginal line and cannot afford an EV unit. The distinction could reach the national level when different societal preferences and benefits are provided to individuals based on having an EV and sharing the V2G scheme, which ensures unfair access and elitism and can further perpetuate inequality across the EV culture [28].

Second, the EV market is becoming more and more dominant in the vehicle manufacturing process. When government policy becomes stricter regarding ICE manufacturers and their taxes are increased per unit sold, it is more likely that the owners of the vehicle manufacturing farms will either need to reduce production or transition to only manufacturing parts for EVs. In either case, the number of active employees and workers needed would be curtailed by a vast number. This can directly result in unemployment and the disruption of traditionally well-matured businesses.

Third, although the use of EVs does not directly warrant emissions, non-renewablebased power plant operation could show a considerable carbon footprint. Moreover, building onboard batteries, mining, processing, and manufacturing results in environmental hazards. Commercial vehicle emissions usually appear as air pollutants and GHGs. A direct and well-to-wheel (W2W) consideration often results in an efficient evaluation of these emissions. ICEs are responsible for direct emissions, whereas the direct emissions from EVs are very insignificant. The W2W emission comprehensively considers the emission associated with various stages of vehicle development, production, manufacturing, and use. The W2W for ICEs is chiefly contributed by extracting petroleum resources, processing and distributing liquid fuel, and burning fuel for ICE propulsion. Since electricity is being used for EVs, the emission relevant to the conventional power plants and extraction of energy sources for power plant operation come into play, which is often significant to consider. In HEV, both the ICE and battery units are considered; this increases the carbon footprint more than BEVs and other battery-driven EV types. It is predicted that by 2030, the HEVs could reduce the CO₂ emission to \sim 250 g/mi, compared to \sim 350 g/mi of ICEs. In China, the CO_2 emitted from HEV was measured to be 121.6 g/km in 2015, while it was anticipated to be reduced to 70.7 g/km by 2030 [29]. In the USA, 5.68 and 1.98 g CO_2 /eq-km emission has been found for the PHEV-AER62 and the PHEV-AER18, respectively [30]. The investigation of the HEV is performed by considering the series, parallel, and hybrid types. Though HEV emits less CO_2 compared to conventional vehicles, it is found from recent research that CO2 emissions from PHEV are as much as two-and-a-half times higher than official tests. For a low carbon grid with PHEV, the emission is about 4.5 lb/vehicle per day, while it is 9.4 lb/vehicle per day for a high carbon grid [29]. It is realized that

the benefit of reducing the carbon footprint by HEV depends on having a low-carbon electric grid. Since the cost of power plant operation varies from country to country, the CO_2 footprint of the same HEV configuration running across different borders could be significantly different. Vehicle powertrain electrification plays a vital role in reducing CO_2 emissions and fuel consumption [31]. Implementing mild-hybrid technologies can provide a cost-effective fuel economy solution, depending on the specifications of the hybrid components and the selected topology [32]. The average CO_2 reduction potential of an MHEV is strongly dependent on the hybrid system configuration (P0 to P5 or combinations), the power and efficiency of the electric machine and battery pack, and driving dynamics and conditions [33]. Mining for raw materials alone is a big culprit in the destruction of large forest areas, equating to higher carbon emissions and considerably disrupting the native ecosystem and human lifestyles. In addition, the disposal of toxic materials such as debris and obsoletes degrades the soil, water, and air surrounding the areas. In [34], the authors have demonstrated that the benefits of EVs are centralized only in the cosmopolitan areas that rely on low air pollutant fuels. Most of the time, the countries or cities where the actual mining and manufacturing process occur and the countries that utilize the EVs as a product are different. Thus, carbon emissions and associated problems are only shifted from one country to another.

Fourth, the EV market, as of now, is not that glittery. For instance, in [30], feedback from the salesperson affiliated with the Nordic automobile dealerships shows that it is much more challenging to retain a profitable business by selling only EV units. Additionally, each EV car takes more time and more effort to sell. The EV retail points are inadequate and lack the technical expertise to supervise most EV-related issues. Shifting employees from ICEs to EV schemes calls for specific training and knowledge dissemination regarding the policies, protocols, and standards, which is very difficult and time-consuming. A business backed by significant investment might cope with slow returns at the beginning stages, but this prevents newer startups from reaching a mature level before becoming extinct. Moreover, independent and locally oriented EV manufacturing farms face a unique disadvantage in extending business due to insufficient sales or the hurdle of competing in an immature market with growing technological advances.

3. Electric Vehicle Technology

3.1. Advancement of Electric Vehicle Technologies

Electric vehicles (EVs) use electric motors and electrical energy for propulsion by providing thrust to the vehicle wheels [1]. The crucial EV components are the drivetrain, electric engines or motors, reducer, battery storage system, onboard charger (OBC), and electric power control unit, as shown in Figure 10 [35]. The electric energy from an AC outlet is converted by the OBC and charges an onboard DC battery energy storage system [36]. During acceleration, DC battery voltage inverts to AC voltage by an inverter and is applied to the electric motor. The controller controls the DC-AC inverter's output AC voltage frequency and maintains the wheel speed as desired. During braking or downhill progression, the regenerative braking causes an inverted motor run; acting as an alternator, the motor charges the battery and increases fuel economy. The magnitude of regenerative braking is manually controllable by paddle shifters mounted over the steering wheel. In DC motor-based EVs, the inverter unit is not used; rather, a low voltage DC–DC converter converts the high battery storage voltage to low voltage (~12 V) to drive the onboard electronic components. A vehicle control unit oversees the process of motor control, power control, power flow to the electronic systems, load management, and regenerating braking in a neutral gear drive.



Figure 10. Main components of an electric vehicle (EV) [35].

Battery storage is vital since higher battery energy density can render a higher driving distance with improved fuel economy and efficiency [37]. This also saves space on the EV board. HYUNDAI reported a 64 kWh Li-ion battery that can deliver up to a 386 km drive. However, the battery's life cycle alters with the EV's charging and discharging pattern [38]. The battery density degradation of EVs often causes slow acceleration and requires to be replaced, resulting in a secondary battery.

Moreover, when the ambient temperature falls below the standard operating range of the battery, the charging capacity and the speed limit are reduced. A battery heating system is usually augmented to minimize the problem. The battery management system (BMS) monitors the charge or discharge level of the battery cells. If a cell's charge or discharge level varies from the string, the BMS employs a relay mechanism to adjust the cell's charge status by connecting or disconnecting other circuits [39]. The driving motor speed of an EV far supersedes the tolerable speed of the wheel. This causes a mismatch in transferring the available motor revolutions per minute (RPM) to the car wheel. A reducer is used to curtail the motor RPM, and the transmission drivetrain could drive the wheel at an appropriately reduced speed and with a higher torque level [40].

The rapid growth of battery storage technology and semiconductor technology has paved an unparallel route to the innovation of different EV systems and curtailed well-to-wheel (WTW) and well-to-tank (WTT) CO₂ emission rates [41]. As a result, vehicle propulsion could be driven by complete or partial utilization of the electric motor and the energy stored in the onboard batteries. As shown in Figure 11, depending on the system architecture, EVs could be classified into all-electric, hybrid, and internal conversion electric vehicles [42]. Figure 12 represents the internal configuration of the most common EV types; battery electric vehicles (BEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV), and solar electric vehicles (SEVs).



Figure 11. Electric vehicle types depending on the architecture of the design [42].



Figure 12. The internal configuration of the five primarily used electric vehicle architectures [43].

A BEV, also referred to as an all-electric vehicle, uses no ICE but instead electric motors, a battery, and a drivetrain to run the vehicle. The battery is charged from a charging point. The output DC voltage of the battery is inverted to AC; its frequency is controlled by the controller signal from the pedal acceleration, which is applied to the wheel through a mechanical cog arrangement. The battery is also recharged during the BEV's regenerative braking operation (RBO). Tesla X, Model-3, BMW i3, and Ford Focus Electric use an all-electric system architecture. In 2020, around two-thirds of all the stocked ~10 million EVs and two-thirds of all the newly registered ~3 million EVs were BEV type. The newly registered BEVs comprised nearly 82%, 80%, 78%, 73%, 62%, and 60% of all the registered EVs across the Netherlands, China, the USA, Norway, the UK, and France, respectively [17]. A BEV unit comes along with a ~55 kWh battery unit, and its usual average price is around USD 40,000.

HEV, the parallel hybrid, exploits battery storage and fuel tank advantages to drive electric motors and ICE, respectively. In real-time, the wheel is rotated via the torque developed by the electric motor and gasoline engine. One crucial uniqueness of the HEV system is that there happens to be no electrical charging port to recharge it using a power grid. Batteries could only be recharged by driving the ICE engine, the RBO of the wheels, or a combination of both. Like the traditional ICE, the fuel tank is refilled from a gas filling point. Honda (Civic Hybrid model) and Toyota (Prius Hybrid model) are leaders in manufacturing HEVs.

PHEV improves the EEV's performance and efficiency significantly. Unlike the HEV, the onboard battery could also be charged from electrical outlets or EV charging stations (EVCSs). This series of hybrid operations provide opportunities to consider renewable (bio-diesel) and non-renewable (gasoline) fuel to drive the vehicle. The vehicle utilizes the all-electric propulsion scheme. When the battery is depleted or after reaching highway cruising speed (~70 miles per hour), the ICE takes over the operation, and the EV acts as a conventional vehicle. The RBO charges the battery at this stage, reducing the vehicle's operating cost. As a result, the onboard battery storage capacity required (~14 kWh) for PHEVs decreases by more than four times the capacity required for BEVs. The average electric range for a PHEV, costing USD 50,000, covers ranges from 40 to 60 km. In 2020, the number of newly registered PHEV units tripled, with an 8% price drop. Globally, among the total 435,000 units of low commercial vehicles (LCVs) in 2020, less than 10% were comprised of PHEVs [17]. Major car companies vastly manufacture PHEVs. Ford: C-Max Energi, Fusion Energi; Mercedes: C350e, S550e, GLE550e; BMW: 330e, i8, X5 xdrive40e; Porsche: Cayenne S E-Hybrid, S E-hybrid, have already made their way to the mass public as an exciting experience.

FCEV exploits the recent improvement of fuel cell technology. From an H_2 charging station, the onboard H_2 fuel tank is filled up, and this H_2 is provided to the fuel cell, where chemical energy is directly converted to electrical energy. The efficiency of fuel cells ranges from 40% to 80%. Energy generated in the fuel cell drives the motor or recharges the battery storage units. Although the FCEV was first introduced to the vehicle market as hype in 2014, the lack of sufficient hydrogen refueling stations (HRS) and unavailability of

household charging facilities have retained the FCEV registration to nearly three orders of magnitude lower compared to EVs. Globally, more than 540 HRS are present to provide services to nearly 35,000 FCEV units. In 2020, the global count of HRS increased by 15%, which helped to increase FCEV stock by nearly 40%. Korea, the USA, China, Japan, and Germany respectively hosts nearly 30%, 27%, 24%, and 12% of the global FCEV units and 9%, 12%, 16%, 25%, and 17% of the global HRS [17]. According to the IEA outlook for 2021, Korea is currently leading the FCEV with the highest number of FCEV stocks, with nearly 10,000 FCEV units [17]. The FCEV is zero-emission, and the operation differs from other EV types. Toyota's Mirai and Hyundai's Tucson FCEV have garnered public attention among other FCEVs.

SEV uses a photovoltaic (PV) panel over the vehicle's top that charges the batteries to drive propulsion and power driving and controlling devices. The solar-powered plug-in hybrid EV has been garnering much attention recently. This is due to the high suitability of the solar-powered charging station [44], parking lots [45], and the vehicle itself [46,47]. The relative advantages and disadvantages of the commonly available EVs are summarized in Table 2 [48].

EVs are also categorized considering the degree of electrification utilized. Figure 13 shows the motor traction power, degree of electrification on a scale of 0% (conventional vehicles) to 100% (full EV), and improved fuel efficiency of common EV types [49]. In a range-extended electric vehicle (REEV), a high-capacity battery pack is used to drive propulsion. A small engine generator charges the batteries that could provide an extended driving range of nearly 100 km per two liters of fuel consumption [50].



Figure 13. Degree of electrification, power of traction motor, and improvement in fuel efficiency of common electric vehicle types [49].

3.2. EV Charging Station

Electric vehicle charging stations (EVCSs) are the most crucial infrastructure part of the successful exploitation of EV technology. Countries such as the US, China, Japan, the UK, and other European nations have dispatched rules and procedures to erect small-to large-scale domestic, public, and commercial EVCSs to improve EV users and reduce carbon footprint [45,51–53]. For example, in 2021, the US government prospected to operate 600,000 charger plugs to power an estimated 18 million electric vehicles by 2030. EVCS provides a simple and fast charging procedure by inserting the plug of the EV connector into the electric outlet. The connector's other end is inserted into the EEV's battery charger inlet to charge the battery units. The electric vehicle supply equipment (EVSE) units generally range from \$300–\$1500, \$400–\$6500, and \$10,000–\$40,000 for Level-1, Level-3, and DC fast charging, respectively. The installation cost of the EVSE directly depends on the site features and the highest charger cost, which could reach from \$3000 (Level-1) to \$51,000 (DC fast charging). The EVCSs are often categorized into the following parts:

- The residential charging station, where the end-user draws the electrical energy. The vehicles–when not in use, especially during night hours–are charged via the wall-mounted indoor outlet;
- The commercial charging station, which is applied to charge the standing vehicles in the parking lots and at public charging places;
- Fast-charging stations (>40 kW), these stations can provide 60 miles of battery backup within 10 to 30 min of charging, which is highly suitable for high-performance EVs;
- Charging stations for zero-emission vehicles (ZEV) can provide 15 min of charging to drive nearly 200 miles. California Air Resources Board (CARB) uses this type to provide credit to non-emissive vehicle users.

Across the globe, a few standards have been driven based on the charging level and power rating considered for EV charging. The North American SAE-K17 [54] and Chinese GB/T 20,234 [55] standards consider the level and power of electrical energy flow during charging. Parts of China and European countries use the IEC-62196 [56] standards, which measure the nominal power used with the charging time. The manufacturing of the components of the EVs also follows strict standards. The Tesla manufacturing farm and the Japanese government considers the CHAdeMO standard for EV charging infrastructure erection and components selection. Apart from that, IEC 61851-1 [57] and IEC 62192-2 [58] standard is comprehensively used worldwide to design the outlets, inlets, connectors, and plugs for EV charging stations. A detailed overview of the currently used EV charging ports and connectors across China, Japan, the USA, and the EU is summarized in ref. [42].

Recently, wireless EV charging stations (WEVCS) are becoming attractive as they provide much safety and convenience compared to standard EVCSs [59]. In WEVCS, the batteries are charged wirelessly through the transformer principle. There is one considerable alteration, however; unlike a power transformer where the frequency is the same on both the primary and secondary sides, WEVCS frequency on each side could differ from the other side's frequency. The 50 Hz power frequency of the primary side is converted to a high-frequency value and is provided to a transformer coil. This forms a strong electromagnetic field, which induces the voltage across the onboard receiver side of the EV charging unit [60]. This induced voltage then charges the batteries. Maximum power is transferred at the resonant frequency of the transmitter and receiver side and is always maintained near that limit by inserting compensating networks on both sides. Figure 14 represents the schematic wired and wireless charging methods of EVs. In static WEVCS, the vehicle is kept stationary during the charging process. In parking lots or the garage, the wireless transmitter is provided under the surface area, and the receiver unit of the EV is mounted on the lower side of the vehicle.



Figure 14. The schematic layout of the wired and wireless charging methods [42].

			Power	Ratings	Charger 1	Ratings	Refs.
EV Technology	Key Features	Key Vulnerabilities	DC	AC	Slow Charger	Fast Charger	
Battery Electric Vehicle (BEV)	 Improved fuel efficiency. Recharge through regenerative braking. 	 Travel distance is short, 210 km to 640 km. Low battery capacity, 65 kWh to 180 kWh. Requires improved battery storage units and charging infrastructure. Vulnerable to cyber-attack. 	4 kW to 22 kW	40 kW to 221 kW	3 h to 13 h	18 min to 90 min	[61]
Hybrid Electric Vehicle (HEV)	 Improved fuel efficiency. Recharge through regenerative braking. Performance is optimized with zero- emission capability. Grid energy utilization is high. 	 The cost is higher, \$5000 to \$10000. Needs two power trains, which render much transmission loss. Associated components need to be available in the market. Challenging energy management system. 	21 kW to 185 kW	-	2 h to 22 h	up to 20 min	[62]
Plug-in Hybrid Electric Vehicle (PHEV)	 Low operating cost. Performance is optimized with zero- emission capability. Recharge through regenerative braking. Quiet operation. 	 The initial cost is higher. Needs two power trains which render much transmission loss. Associated components need to be available in the market. Battery cost is higher. Weight is higher than HEV. Unable to charge on a fast charger. 	1 kW to 19 kW	50 kW to 350 kW	1.5 h to 20+ h	-	[63]
Fuel Cell Electric Vehicle (FCEV)	 No emissions. Fuel efficacy is very high. The battery can be recharged through regenerative braking. No petroleum fuel is required. 	 The operating cost is higher, \$58,300 or \$379-\$389/month. Need improved Hydrogen refueling station. H2 Storage is cumbersome. Mass production is limited. Lesser durability. 	100 kW	-	refueled in 5 min	-	[64,65]
Solar Electric Vehicle (SEV)	 No emissions. Conversion efficiency is higher than traditional ICE. The battery can be recharged through regenerative braking. No petroleum fuel is required. 	 Driving range is limited to 350 km. Power production is low. The cost of the vehicle is higher. Dependence on the solar trajectory. Reduced output due to weather vulnerability. 	2 kW to 22 kW	50 kW to 300 kW	4 h to 7 h	20 min	[66]

Table 2. Comparison among commonly used electric vehicle architectures [48].

On another front, in dynamic WEVCS, the wireless charging process occurs when the car is running. Thus, the battery could be charged during the travel while discharging, reducing the battery size and capacity. Depending on the operation, the WEVCS is classified as an inductive wireless charging station (IWCS), capacitive wireless charging station (CWCS), permanent magnet-gear wireless charging station (PMWCS), and resonant wireless inductive charging station (RIWCS) (Table 3).

 Table 3. Operation-based category of wireless electric vehicle charging stations.

Category	Key Features	Auxiliary Units	Wireless Charging Range (Distance, Frequency)	Wireless Power Transfer Class	Refs.
Inductive wireless charging station (IWCS)	 Power is transmitted through transmitter-receiver sets. Faraday's law of electromagnetic induction is used. Operating range: 19 to 50 kHz. 	Power factor correction circuit, h-bridge, rectifier, and filter	Operating range: 19 to 50 kHz Distance: 1.5 cm or less	WPT1: 3.7 kVA	_
Capacitive wireless charging station (CWCS)	 No transmitter-receiver sets. Power transmitted through. Capacitive coupling. Uses the electrostatic induction principle. Operating range: 100 to 600 kHz. 	Magnetic gear, rectifier, and filter	Operating range: 100 to 600 kHz.	WPT2: 7.7 kVA	[67, 70]
Permanent magnet-gear wireless charging station (PMWCS)	 Power is transmitted through transmitter-receiver sets. Armature winding and a permanent magnet are provided in the transmitter-receiver unit. Works as a wirelessly coupled motor generator. 	Rectifier and filter	Operating range: up to 150 Hz (for 1 kW)	WPT3: 11 kVA	- [0/-/0]
Resonant wireless inductive charging station (RIWCS)	 A resonator with a high-quality factor is used for wireless charging. A compensation network is provided to match transmitter-receiver coils. 	Series-parallel compensating units, rectifier, and filter	Operating range: 10 Hz to 150 Hz	WPT4: 22 kVA	_

3.3. V2G System

With time, EV technology may impact the prevalent transportation, electrification, control, communication, and artificial intelligence technologies. The recent introduction of the microgrid and smart grid concepts has engendered a few sophisticated ways to improve the overall power system operation via implementing vehicle-to-grid (V2G) technology, wherein a sustained communication framework and control and management protocols help electrical power exchange between the EV and power grid. V2G is one of the three emerging grid-connected EV schemes–vehicle-to-home (V2H), vehicle-to-vehicle (V2V),

and vehicle-to-grid (V2G)–proposed in the literature to exploit the housed battery storage systems of the EVs [71]. Figure 15 demonstrates a typical framework of the V2G system.

The vehicle-to-grid (V2G) technology uses EVs as a power supplier and adjuster in the power grid, while electricity from the grid can be taken as a load and serve as a source to the grid when in need. In addition, it can be used as a renewable energy source by drawing unused power from the EV into the grid with sufficient coordination, improving power efficiency, stability, and reliability. In developing countries, the type of fuel (coal, gas, HFO, HSD, and others) used for generation is costly and hazardous to the environment. An EV can also be a greener alternative for these countries where power is much needed at a lower cost.

For about 5% of the whole day, a car remains on the road [72]; the remaining time, it is either parked on the office premises or rested in the domestic car garage. When idle, it can be easily connected to the grid and used as a power source for domestic purposes. More specifically, when solar power is unavailable at night, V2G technology greatly supports the generation plants that offer reactive power support, active power regulation, tracking of variable renewable energy sources, load balancing, and current harmonic filtering [38]. Besides serving as a power source, vehicle-to-grid technologies can facilitate ancillary services, such as voltage and frequency control and spinning reserve [2,73]. There are supposedly three features essential for a V2G-enabled vehicle [36]: power supply, communication systems for the grid to access the vehicle's power, and a high-precision measurement system to track the power flow.



Figure 15. Vehicle to basic grid framework [74].

In the V2G technique, power flow between the grid and the EV is constantly monitored and controlled to ensure economical operation while maximizing profit and reducing GHGs emissions [75]. The power flow of the V2G is primarily classified into a unidirectional and bidirectional model (Table 4).

In the unidirectional arrangement of the V2G, a simple charge controller stage is required in the EV battery fleet to charge the batteries, and the power flows between the grid and the EV in a single direction (Figure 16) [76]. In this mode, the EV fleet could increase the spinning reserve of the power system. Moreover, the grid voltage and frequency regulation can also be controlled by ensuring proper power flow control [77]. In this context, aggregator's profit maximization algorithms have been proposed in the literature for unidirectional V2G mode [78]. These algorithms exploit the energy trading policy between the power utility and EV owners [79]. Proper flexibility of the grid operation is ensured by dispatching auspicious revenue packages for the EV owners to provide V2G



power during peak load demands. Although the unidirectional V2G mode is easy to implement, it has limited ancillary service capabilities.

Figure 16. Unidirectional and bi-directional power flow architecture in V2G technology with charger power rating [76].

In bidirectional V2G mode, power flows in both directions and can be used to shave peak load demands and provide reaction vars and v-f regulation. However, the bidirectional operating mode requires additional power electronic converter AC/DC and DC/DC stages (Figure 17) [76]. The AC/DC mode operates in both directions during the charging and discharging mode of the EV. The DC/DC stage is required for proper current control and works as a buck and boost converter during the charging and discharging phases. These dynamic power electronic stages make it possible to integrate renewable distributed sources. In addition, the intermittent problem of the renewables could be lessened by using the EV BESS as the buffering stage under contingent weather conditions. However, in the bidirectional V2G mode, the charging and discharging process degrades the lifetime of the BESS and requires a complex charge controller and controlling mechanisms [80].

The V2G system might significantly impact the current power grid infrastructures worldwide. EVs are mostly connected across different regions via residential or commercial charging stations where both slow and fast charging could be implemented. Slow charging-levels 1 and 2–is prevalent in residential places, whereas fast charging–level 3–and DC charging are prevalent in commercial EV refueling. Figure 17 represents the operating schematics of a V2G technology [73]. It is crucial to realize the charging–discharging features and lifetime of the battery storage onboard the EVs. Table 5 summarizes the key specifications of the commercially available EV models globally and their housed onboard battery storage features.



Distributed EVs and chargers

Figure 17. Components and power flow of V2G system with PEV [73].

	Component	Rating of Smart	Wireless	Rating of Wireless		Power	Requirement		
	Requirement	Meter	Communication Technology Used	Communication Technology	Control Strategy Used	DC	AC	Cost	Refs.
Unidirectional V2G	Utility gird, Electric Vehicle, State of charge controller,	-	IEEE 802.11p	5.85–5.925 GHz, 3 to 27 Mb/s (Data Rate) over a bandwidth of 10MHz, 1–1000 m	Real-time smart load management (RT-SLM); Virtual Synchronous Machine Control (VSM); Multi-Agent Control (MAC);	50 kW-250 kW	1-phase: 240 V, 15 A, up to 4 kW;	Without EV: \$7.07/kWh	[43,81-85]
(venicle-to-grid)	AC-DC converter, DC-DC converter,		IEEE 802.15.1	2.4 GHz, 1–100 m	Fuzzy Logic Controller (FLC)		3-pnase: 20 A, 14.4 kW, up to 250 kW	\$ 8.17/kWh	
	Controller, Battery storage		Converged fiber wireless (Fi-Wi) communications *	5 GHz, 10 Gb/s, 1–40 m (indoor)	-		-		
	Utility and Elastria		ZigBee 868	MHz (Europe) 10–100 m 915 MHz (North America) 2.4 GHz (Worldwide)					
Bi-directional V2G	Vehicle, bi-directional charger, Controller,	VT: 0-600V	Near Field Communication (NFC)	GHz (Worldwide) Near Field mmunication 13.56 MHz, 5–10 cm (NFC) Model predictive control		1-phase: 0 to 7 kW:	\$399 to \$3600		
(vehicle-to-grid and grid to vehicle)	Battery storage, DC-DC converter.	Internal Resistance:	Bluetooth	2.4 GHz	 algorithm; Aggregated Control Strategies 	7.4 kW–19.2 kW	3-phase: 7 kW to 22 kW	(charger cost)	[86–90]
0	DC-AC converter, AC-DC converter,	25 ohm	IEEE 802.11p	5.85–5.925 GHz, 500–1000 m	0				
AC	AC -AC converter		WiMAX	2–6 GHz	-				
			Converged fiber wireless (Fi-Wi) communications *	5 GHz, 10 Gb/s, 1–40 m (indoor)	-				

Table 4. Comparison among commonly-used electric vehicle architectures [48].

* Currently under development.

Table 5. Specifications and features of the commercially available electrical vehicles and ratings of the onboard battery storage [91,92].

V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack
Chevrolet Bolt EV	2022	USA (Chevrolet)	417 km	65 kWh	11 kW	55 kW	~247 km/h	Lithium-ion battery	3 h at 115 V AC 15A	120 V, 240 V	50 kg	3 Li-ion packs, one for hybrid, two for EV
Chevrolet Bolt EV	2022	The USA, South Korea (Chevrolet)	398 km	65 kWh	11 kW	-	-	Lithium iron phosphate	7 h at 240 V AC	120 V, 240 V	430 kg	288 cells
Audi Q4 e-tron	2021	Germany (Audi)	488 km	82 kWh	11 kW	126 kW	~525 km/h	Lithium-Ion	3 h at 230V AC 16 A	450 V	350 kg to 500 kg	10 or 12 modules containing the individual battery cells in an aluminum casing

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V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack
BAIC EU5	2018	China (BAIC)	416 km	53 kWh	7 kW	60 kW	~330 km/h	Ternary lithium-ion battery	9 h	-	380 kg	-
BAIC LITE	2018	China (BAIC)	300 km	30 kWh	7 kW	60 kW	~420 km/h	Ternary lithium battery	-	-	142 kg	-
BJEV EC3	2019	China (BAIC)	301 km	30.7 kWh	7 kW	60 kW	~412 km/h	Ternary lithium battery	9 h	220 V	-	-
BJEV EX3	2019	China (BJEV)	501 km	61.3 kWh	7 kW	60 kW	~343 km/h	Lithium-ion Electric	10 h	120 V, 240 V AC	-	-
BJEV EC5	2019	China (BJEV)	403 km	48 kWh	7 kW	60 kW	~353 km/h	Ternary lithium battery	8 h 42 min at 230 V AC 16 A	230 V	353 kg	-
BMW i4	2021	Germany (BMW)	590 km	83 kWh	11 kW	200 kW	~995 km/h	Pressure lithium-ion	8 h 45 min at 380 V AC 16 A	398.5 V	550 kg	High-pressure lithium-ion 83.9 kWh, four modules with 72 cells each and three 12-cell modules
BMW iX	2021	Germany (BMW)	630 km	111 kWh	11 kW	200 kW	~795 km/h	Lithium-ion battery	10.5 h on 240V AC 48 A	-	-	-
BOLLINGER B2	2021	USA (BOLLINGER MOTORS)	322 km	120 kWh	-	-	-	Lithium-ion	10 h at 220 V	350 V, 700 V	-	The Bollinger Motors battery pack is composed of modules in 35 kWh strings that can be connected in series or parallel to form a variety of pack sizes and configurations.
BOLLINGER B1	2021	USA (BOLLINGER MOTORS)	322 km	120 kWh	-	-	-	Lithium-ion	10 h at 110 V, 220 V	110 V, 220 V	-	8 110 V outlets and 1 220 V outlet
Brilliance Auto H230	2017	China (Brilliance Auto)	158 km	24 kWh	7 kW	60 kW	~277 km/h	Lithium-ion battery	14 h 49 min at 230 V, 10 A	-	250 kg	-
BYD Song Pro EV	2019	China (BYD)	405 km	71 kWh	7 kW	60 kW	~240 km/h	Lithium iron phosphate	12 h 52 min at 230 V, 16 A	-	-	lithium-ion battery cells are made of LFP cathodes
BYD E5	2018	China (BYD)	405 km	51.2 kWh	7 kW	60 kW	~332 km/h	Lithium iron phosphate	8 h 08min	604.8 V	365 kg	168 single cells are divided into 13 battery modules connected in series; each module has a single battery inside, and the nominal voltage of every single battery is 3.2 V

V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack
BYD S2	2019	China (BYD)	305 km	40.62 kWh	7 kW	60 kW	~315 km/h	Ni-Co lithium manganate battery	6 h 27 min	-	-	-
BYD Qing Super Version Pro EV	2020	China (BYD)	520 km	69.5 kWh	7 kW	60 kW	~314 km/h	Ternary lithium battery	132.75 min	-	-	-
BYD Full New Yuan	2019	China (BYD)	305 km	40.62 kWh	7 kW	60 kW	~315 km/h	Ternary lithium battery	6 h	800 V	-	LFP chemistry and cell-to-pack system
BYTON M-Byte	2019	China (BYTON)	402 km	71 kWh		150 kW	~595 km/h	lithium-ion battery	4.5 h	110 V, 120 V	-	-
Changan EV460	2018	China (Changan)	430 km	52.56 kWh	7 kW	60 kW	~344 km/h	lithium iron phosphate	8 h	-	372 kg	-
-Changan CS15EV400	2019	China (Changan)	351 km	42.92 kWh	7 kW	60 kW	~343 km/h	ternary lithium battery	6 h 49 min	-		-
Chery Tiggo3xe	2018	China (Chery)	401 km	53.6 kWh	7 kW	60 kW	~314 km/h	ternary lithium battery	8 h	-	395 kg	built from the most advanced NMC cells
Chery eQ1	2020	China (Chery)	301 km	30 kWh	4 kW	50 kW	~351 km/h	ternary lithium battery	7 h	-	226 kg	pouch-type cells with an energy density of 140.2 Wh/kg
Dongfeng S50 EV	2018	China (Dongfeng)	410 km	57 kWh	7 kW	60 kW	~302 km/h	lithium-ion battery	11 h	-	359 kg	-
Fiat 500	2020	Italy (Fiat)	320 km	42 kWh	11 kW	85 kW	~453 km/h	lithium-ion battery	14 h	12.6 V	100 kg	-
Ford Mustang Mach-E	2020	Mexico, USA (Ford)	610 km	98 kWh	11 kW	150 kW	~654 km/h	lithium-ion battery	10.1 h	120 V, 240 V	485 kg	288 lithium-ion cells in the standard-range version and 376 lithium-ion cells in the extended-range
Tesla Model Y	2020	USA (Tesla)	480 km	75 kWh	11 kW	250 kW	~1120 km/h	lithium iron phosphate	8 h 15 min	400 V	363 kg	2170 cells with NCA chemistry
Tesla Roadster	2022	USA (Tesla)	998 km	200 kWh	22 kW	250 kW	~873 km/h	lithium-ion battery	10 h 45 min	375 V	833 kg	6831 lithium-ion batteries, cells size: 18mm in diameter by 65mm long
Tesla Cybertruck	2022	USA (Tesla)	805 km	200 kWh	11 kW	250 kW	~704 km/h	lithium-ion battery	21 h 30 min	120 V, 240 V	1406 kg	-

V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack
Tesla Model 3	2019	USA, China (Tesla)	560 km	82 kWh	11 kW	250 kW	~1195 km/h	lithium-ion battery	12 h 15 min	120 V, 240 V, 480 V	480 kg	four longitudinal modules, each containing the groups (bricks), the Standard Range version carries 2976 cells arranged in 96 groups of 31
Tesla Model Y	2020	USA, China (Tesla)	505 km	74 kWh	11 kW	250 kW	~1194 km/h	lithium-ion battery	-	-	-	4416 cells
Tesla Model X	2019	USA, Holland (Tesla)	580 km	100 kWh	16 kW	250 kW	~1015 km/h	lithium-ion battery	6 h 30 min to 10 h	240 V	625 kg	around 444 Panasonic NCR18650B cells running in 74p6s configuration
Geely EV500	2019	China (Geely)	500 km	62 kWh	7 kW	60 kW	~339 km/h	lithium-ion battery	9 h	220 V	-	Ternary Lithium Battery + 3.0 ITCS Intelligent Temperature Control Management System
Geely Gse	2019	China (Geely)	450 km	61.9 kWh	7 kW	60 kW	~305 km/h	lithium-ion battery	9 h	220 V	-	-
Haima E3	2018	China (Haima)	315 km	46.6 kWh	7 kW	60 kW	~284 km/h	lithium-ion battery	9 h	-	331 kg	-
Haima EV	2018	China (Haima)	202 km	21 kWh	7 kW	60 kW	~404 km/h	lithium-ion battery	-	-	293 kg	-
Hanteng Auto	2018	China (Hanteng)	252 km	42.7 kWh	7 kW	60 kW	~248 km/h	lithium-ion battery	6 h 47 min	-	-	-
Honda e	2019	Japan (Honda)	222 km	35.5 kWh	6.6 kW	56 kW	~245 km/h	lithium-ion battery	5 h 45 min	230 V	-	-
Honda Clarity Electric	2017	USA (Honda)	143 km	25.5 kWh	6.6 kW	80 kW	~314 km/h	lithium-ion battery	3 h 30 min	120 V, 240 V	100 kg	-
GMC Hummer EV	2022	USA (Hummer)	560 km	200 kWh	_	-	-	Altium- powered and lithium-ion battery	3 h 20 min	120 V	1325 kg	24 individual battery modules with wireless management and parallel cooling systems
Hyundai Ioniq 5	2022	South Korea (Hyundai)	485 km	72 kWh	11 kW	221 kW	~1042 km/h	lithium-ion battery	6 h 43 min	800 V	450 kg	12 pouch cells and stores about 2.4 kWh of energy
Hyundai Kona Electric	2021	South Korea (Hyundai)	449 km	64 kWh	11 kW	77 kW	~378 km/h	lithium-ion polymer battery	9 h 35 min	356 V	453.6 kg	paired with an electric motor that delivers 204 PS (150 kW)

V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack
Hyundai Ioniq Electric	2019	South Korea (Hyundai)	311 km	40 kWh	7 kW	44 kW	~239 km/h	lithium-ion polymer battery	13 h	360 V	271.8 kg	96 battery cells arranged in 12 modules
JAC iEVS4	2019	China (JAC)	355 km	55 kWh	7 kW	60 kW	~271 km/h	lithium-ion battery	-	-	-	-
Jaguar I-PACE	2017	Austria (Jaguar)	480 km	90 kWh	7 kW	100 kW	~373 km/h	lithium-ion battery	10.1 h	240 V	610 kg	432 pouch cells in 36 modules that use nickel-manganese- cobalt battery chemistry.
Kia EV6	2022	South Korea (Kia)	490 km	77 kWh	11 kW	233 kW	~1038 km/h	lithium-ion phosphate (LFP) battery	7 h 10 min	697 V	477 kg	Nickel-Cobalt- Manganese (80/10/10)
Kia Niro EV	2019	South Korea (Kia)	455 km	64 kWh	7.2 kW	77 kW	~383 km/h	Lithium Ion Polymer Battery (LIPO)	10 h 30 min	356 V	457.22 kg	-
Lifan 820EV	2018	China (Lifan)	330 km	60 kWh	7 kW	60 kW	~231 km/h	ternary lithium battery	10 h 52 min	320 V	420 kg	-
Lucid Air	2022	USA (Lucid)	660 km	112 kWh	19 kW	300 kW	~1238 km/h	lithium-ion battery	13 h	240 V	-	thousands of 21700-format cylindrical cells
Mazda MX-30 EV	2020	Japan (Mazda)	210 km	35.5 kWh	6.6 kW	50 kW	~207 km/h	lithium-ion battery	5 h 30 min	355 V	-	-
Mercedes EQS	2022	Germany (Mercedes)	770 km	120 kWh	11 kW	207 kW	~930 km/h	lithium-ion battery	11.25 h	400 V	-	NCM 811 lithium-ion; Nickel, Cobalt, and Manganese in the ratio of 8:1:1,8 to 10 cells depending on the configuration and features a liquid thermal management system
Mercedes EQC	2019	Germany, China (Mercedes)	417 km	80 kWh	11 kW	112 kW	~409 km/h	lithium-ion battery	11 h	-	650 kg	384 cells—two modules with 48 cells and four modules with 72 cells
Mercedes EQB	2022	Germany, China (Mercedes)	419 km	69 kWh	11 kW	113 kW	~480 km/h	lithium-ion battery	7 h 15 min	400 V	_	-
Mercedes EQA	2021	Germany (Mercedes)	426 km	69 kWh	11 kW	112 kW	~484 km/h	lithium-ion battery	7 h	400 V	-	200 cells arranged in five modules
MG ZS EV	2020	India (MG Motors)	262 km	44.5 kWh	6.6 kW	80 kW	~330 km/h	Nickel Manganese Cobalt (NMC) battery	7 h 45 min	230 V	250 kg	44.5 kWh liquid-cooled battery pack (CATL cells)

V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack
MINI Cooper SE	2020	UK (Mini)	235 km	32 kWh	11 kW	49 kW	~252 km/h	lithium-ion battery	3.5 h	120 V	145 kg	12-packs of lithium-ion cells arranged in a T-shape
NIO ES6	2019	China (NIO)	510 km	84 kWh	7 kW	60 kW	~255 km/h	lithium-ion battery	10 h	220 V	635 kg	-
Nissan Leaf	2019	Japan, USA, UK (Nissan)	385 km	62 kWh	6 kW	100 kW	~435 km/h	lithium-ion battery	11.5 h	360 V	303 kg	192 cells; 2 in parallel and 96 in series, arranged in 24 modules
Nissan Ariya	2021	Japan (Nissan)	500 km	87 kWh	22 kW	130 kW	~523 km/h	lithium-ion battery	4 h 45 min	400 V	-	-
Nissan e-NV200	2018	Japan (Nissan)	200 km	40 kWh	6.6 kW	50 kW	~175 km/h	lithium-ion battery	8 h	360 V	267.5 kg	48-module compact lithium-ion battery, each module contains four cells
Opel Corsa-e	2019	France (Opel)	330 km	50 kWh	11 kW	100 kW	~462 km/h	lithium-ion battery	7 h 15 min	230 V	-	-
Polestar 2	2020	China (Polestar)	500 km	78 kWh	11 kW	150 kW	~673 km/h	lithium-ion battery	8 h 15 min	400 V	-	324 pouch cells, 27 modules, liquid-cooled
Porsche Taycan	2021	Germany (Porsche)	456 km	93.4 kWh	11 kW	262 kW	~895 km/h	lithium-ion battery	9 h	800 V	630 kg	33 cell modules consisting of 12 individual cells each (396 in total)
RedStar Auto	2018	China (RedStar)	252 km	32.7 kWh	7 kW	60 kW	~324 km/h	lithium-ion battery	5 h 11 min	-	220 kg	-
Renault Kangoo Z.E.	2017	France (Renault)	270 km	33 kWh	7.4 kW	-	-	lithium-ion battery	8 h 45 min	400 V	255 kg	192 cells in 12 module
Renault ZOE	2020	France (Renault)	390 km	52 kWh	22 kW	50 kW	~263 km/h	lithium-ion battery	1 h	230 V	326 kg	192 cells; 96 in series, 2 parallel
Renault Twizy	2012	Spain (Renault)	100 km	6 kWh	3 kW	-	-	lithium-ion battery	3 h 30 min	220 V-240 V	100 kg	-
Rimac Nevera	2021	Croatia (Rimac)	550 km	120 kWh	22 kW	500 kW	~1604 km/h	Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2)	17 h 22 min	800 V	-	Cell format: cylindrical 2170 number of cells: 6960
Rivian R1S	2021	USA (Rivian)	660 km	180 kWh	11 kW	160 kW	~411 km/h	lithium-ion battery	26 h 2 min	400 V	-	9 modules, 2170-type cylindrical cells (7776)
Rivian R1T	2021	USA (Rivian)	644 km	180 kWh	11 kW	160 kW	~401 km/h	lithium iron phosphate	12 h	400 V	-	9 modules, 2170-type cylindrical cells (7776)

Table 5.	Cont.
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V Models	Years of Production	Country of Manufacture	Range	Battery Pack Capacity	Max Charging Power (AC)	Max Charging Power (DC)	Avg. Charging Speed (DC)	Battery Chemistry	Charging Time	Charging Voltage	Battery Weight	Battery Pack	
SAIC MAXUS	2019	China (SAIC)	350 km	52.5 kWh	7 kW	60 kW	~280 km/h	lithium-ion battery	8 h 20 min	-	-	-	
Škoda Citigo iV	2019	Slovakia (Skoda)	265 km	36.8 kWh	7.2 kW	40 kW	~202 km/h	lithium-ion battery	4 h 08 min	-	248 kg	168 cells	
Škoda Vision IV	2020	Slovakia (Skoda)	500 km	83 kWh	11 kW	125 kW	~527 km/h	lithium-ion battery	6 h to 8 h	230 V	248 kg	-	
Smart EQ	2019	France (Smart)	153 km	17.6 kWh	22 kW	-	-	lithium-ion battery	3 h	400 V	-	-	
Sono Sion	2020	Germany (Sono)	255 km	35 kWh	22 kW	50 kW	~255 km/h	lithium-ion battery	2.5 h	230 V	250 kg	-	
Volvo XC40 Recharge	2020	China (Volvo)	400 km	78 kWh	11 kW	150 kW	~538 km/h	lithium-ion battery	5.5 h	120V, 240 V	-	78 modules of 12 lithium-ion cells configured in three parallel stacks	
VW I.D. Crozz	2020	Germany (VW)	500 km	83 kWh	-	150 kW	~633 km/h	lithium-ion battery	7.5 h	240 V	-	-	
VW ID.4	2021	Germany (VW)	482 km	77 kWh	11 kW	126 kW	~552 km/h	lithium-ion battery	7.5 h to 11.5 h	400 V	309 kg	288 cells in 12 modules	
VW ID.3	2020	Germany (VW)	426 km	62 kWh	11 kW	100 kW	~481 km/h	lithium-ion battery	6 h 15m	400 V		12 battery modules, each containing 24 cells	
VW e-Up!	2020	Slovakia (VW)	260 km	36.8 kWh	7.2 kW	40 kW	~198 km/h	lithium-ion battery	5 h 30 m	230 V	248 kg	168 cells	

The Authors accumulate the data presented in this table as a reference for future investigation and consideration.

3.4. Impact of V2G on the Power System

3.4.1. Improved Power Demand Management

The best advantage of inclining towards the V2G technology is the permissibility of the EV to scheduled charging/discharging. The EV could be plugged in during the off-peak periods when the generation exceeds the load demand, and surplus energy could be utilized for charging the EV. Similarly, the EV could provide electrical energy back into the power grid using appropriate converter stages and controller algorithms to meet the peak load demand, thus reducing costly peak power plants. Scheduling EV charging at off-peak hours improves load demand and thus reduces the cost of generation [93]. The V2G technique could prevail in the electric system with load handling capabilities including but not limited to load shifting, flexible load, valley filling, peak clipping, power conservation, and load building [42]. Figure 18 shows the promising characteristics of a single V2G connected to a power grid in reducing the load burden of the power plants [94].



Figure 18. Vehicle-to-grid technology curtailing the peak power plant requirements [94].

In [95], it is obtained that strategic domestic energy storage in V2G-capable EVs, provided with dynamically coordinating control algorithms, could shave the peak power demand up to ~37%. This scheme, in a way, reduces the requirement of additional energy storage elements for contingent load burden and makes power management more economical. In addition, a third-party cyber insurance-based model has recently been reported; it is composed of optimal energy cost and a Markov decision process framework that provides guaranteed information regarding the best charging/discharging schedule at all times and helps to garner the highest profit for the user [74].

Whenever the power demand increases at a certain period, the need for extra energy could be provided by integrating a few EV fleets, kept on standby for similar scenarios. This can significantly improve the control of the power flow. In addition, using a bidirectional AC/DC and DC/DC converter with a standard DC link can make it possible to embed EVs in a microgrid system; a coordination control strategy is often used with a small EV fleet, like a parking lot arrangement [96]. In [97], a home energy management system (HEMS) is used to monitor the economy in dispatching V2G and V2H service during off-peak and on-peak time, respectively, and observed an 11.6% reduction in monthly electricity bills by a mixed use of both services.

Moreover, V2G could promote renewable energy-based microgrids and smart grid systems. In [98], it is indicated that for a small-scale microgrid–composed of an EV parking

lot, dynamic loads, and photovoltaic arrays all connected through a point of common coupling (PCC)–that dynamic programming technique could lead to efficient utilization of the EV management (EVM) system and energy management system (EMS) to provide adequate projection and economic optimization of V2G and G2V profiles. In the presence of an economic-oriented optimization model, consideration of a superstructure of hybrid PV solar cells, wind turbines, hydrogen fuel cells, energy storage equipment, PEV fleet, and distributed generator, the total sustainability cost could be reduced by 39% [99].

3.4.2. Power Quality Improvement

The application of the V2G technology is very viable in improving the power quality, especially when considering a modern microgrid or smart grid with distributed renewable sources. However, due to the intermittent nature of the DERs, they inject harmonics and voltage surges. Moreover, voltage imbalance and flickering also occur with varied reactive power flow. By devising proper unified control algorithms for the EV, onboard charge control equipment such as a synchronous compensator (STATCOM) and active power filter (APF) could be implemented [100,101]. Then, by adequately driving the system, most of the problems associated with DERs could be smoothened out.

In [72], it is shown that when two electric vehicles are integrated with a lab-scale microgrid system, the transient power imbalance during charging and discharging rates stays within the standard limits in both single-phase and three-phase scenarios. Furthermore, in local home electric grid integration with EV, a bidirectional battery charger is also utilized as an active filter to maintain the power quality of the grid under stability limits [102].

3.4.3. Regulation of Power Frequency, Reactive Power Injection, and System Voltage

One of the significant advantages of aggregating EV fleets to the grid is the ability to respond quickly to changing voltage and frequency. V2G could feasibly be applied for v-f controlling to offset grid frequency and voltage deviation from the prescribed limits. In addition, by injecting voltage from the onboard battery storage systems, EVs could improve the grid's voltage level, thus regulating the reactive power flow in a bidirectional manner [103]. This also helps absorb ramp power and provides a spinning reserve for isolated electric networks.

3.4.4. Support for RES

The environment-friendly and onboard energy storage within the EV could support RES. The EV could act as a buffer for intermittent renewable power sources; when the environment is not perfect for garnering enough electrical energy, using the energy from the battery of the EV fleet could meet the extra load demand. Usually, a boosted DC/DC converter is used with a proper motor drive to extract DC link voltage from the EV battery. This voltage is then fed to an active H-bridge power electronic inverter stage. Control algorithms in proportional-and-resonant controllers then control the output voltage and frequency. In addition, an additional buck converter could provide a DC link of 5 V direct voltage to operate the EV onboard peripheral devices [104]. In a microgrid, the electric power injection point across various remote renewable energy sources could be coupled with household or industrial EV parking lots where bidirectional power transmission is permissible. The microgrid operation's overall stability and load dispatch could be applied more feasibly with V2G. Similar to power injection from other distributed renewables, the power flow from the EV to the power grid could be conceptualized through the cost vs. penetration depth flexibility supply curve, shown in Figure 19 [94].



Increasing Renewable Energy Penetration



4. Challenges of V2G

4.1. Burden on the Utility Grid

Loading the EV fleet to the grid is the basic concept for employing the V2G technique. A time-of-day tariffs framework highlights the peak hours in the morning and evening and the off-peak hours and helps to employ V2G during peak hours and G2V during off-peak hours [105]. The process, however, could strain the power grid if not correctly scheduled. Unscheduled power insertion from the EV fleet alters the electrical parameters such as voltage drops, current, line losses, and system harmonics. The magnitude of the burden largely depends on the number of EVs, their tolerable power handling capability, charging and discharging cycle, time of usage, and the discharge pattern. When power is loaded from the vehicle to the utility distribution grid, inserting the EV fleet only when needed and to the required level is crucial. A surge in voltage level could burden the grid's protective switchgear equipment and connected loads. In addition, using EV battery energies during the off-peak hour may badly hamper the power distribution operation since the current grid system seldom could fulfill the demand from 20–30% of EV loading.

In a V2G scheme, if the primary power generation station fails, tremendous load burden shifts onto the EV fleet, thus increasing power demand at the EV outlet [106]. If it lacks protective tripping and protection, the EV batteries could be ruptured. Moreover, lacking proper scheduling of the EV fleet could engender a power loop between the EV units across a region [106]. The energy supplied from higher capacity EV batteries would be used to charge other batteries, which is uneconomical. Conventional EVs provide 12 h of an extended charging period; thus, if all the EVs that are to be connected to the grid are not adequately charged, the power loop will reduce the V2G benefits [8]. In the bidirectional V2G scheme, the loading of EVs depends on the charging modes; in the dump charging mode, only 10% of EVs could be integrated, whereas around 40% EV could be accommodated through the smart charging mode [107].

In the presence of distinct charging and discharging algorithms to cope with load demand, the rendered voltage level varies across different EVs. Since EVs impact the power grid profile to a higher degree than the traditional loads, unbalanced output voltages could result in system imbalances, altered reserve margins, reliability issues, and voltage instability [108]. Therefore, controlled discharging is necessary.

4.2. Increase in System Harmonics

While coordinated and efficiently managed scheduling of the EV to the power grid is feasible to control and maintain power grid stability, it backfires if maintained sporadically. This is because most EVs are connected to the power grid, and at the distribution point, most are in single-phase systems [109]. If the V2G system is implemented and its heavy demand loads any single phase of the three-phase system explicitly, it may create an unbalanced three-phase system with large voltage sags, altering the voltage and current flow [110]. Moreover, the harmonics associated with the power electronics converter stages

can also be injected into the grid, disrupting the grid frequency. It has also been observed that the highest total harmonic distortion from the EV battery charge controller, produced in the summertime, is ~0.37% [111].

A large EV fleet's sudden charging/discharging while implementing the V2G technology would make voltage drops/surges that cannot be settled immediately and may cause stability issues. Finally, during V2G operation, the extra power injection to the grid needs to be carefully maintained; if not, the power overloading may disrupt the transformers, grid components, and protective equipment [112].

4.3. Battery Lifetime Degradation

Although the majority of the extraordinary features of V2G involving ancillary services– such as frequency regulation, peak shaving, spinning reserves, and supporting the DERs– are fascinating, V2G operation directly depends on the capacity and durability of the housed battery storage devices of the EVs [113]. In V2G technology, having a proper control system algorithm, the charging/discharging cycle of the vehicle to the grid could change and vary rapidly since the primary system parameter–the connected load to the grid–is time-variant [114]. Rapid charging/discharging could degrade the battery lifetime; thus, the economic feasibility of using battery storage for longer times becomes affected [115]. Moreover, recycling outdated batteries and managing old and low-capacity batteries is also an economic burden. During gear changing and controlling, the onboard battery plays a crucial part [116]. Thus, the battery needs proper monitoring. The battery charger needs to have the most sophisticated control algorithms to maintain the most economical operation, which becomes difficult with random EV integration into the grid.

4.4. Communication System and Cyber Vulnerability

The communication technique of V2G is quite distinct from conventional communication systems, mainly because of the dependence on the vehicle maneuver, speed, and position in real-time, charging and discharging protocols, and narrow real-time communication range across the network. The transmitter and receiver entity authentication should be secured, fast, and efficient during the communication setup. Moreover, while dispatching dynamic charging/discharging procedures, the communication system needs to be cost-effective and scalable to meet the continually growing colossal number of EVs and their penetration to the UG. EVs could be connected to UG in a centralized or decentralized manner.

The emergence of next-generation sensors, wearable devices, communication devices, and electrical systems suppresses the conventionally used embedded system and controllers. To this end, newer cyber-physical systems (CPS) are being considered. The cyber-physical system will make the building block of the charging infrastructure, EV operation schedule, and communication platform between the charging infrastructure and the EV users. The application of CPS in the EV comprises three basic concepts. First is a blockchain-based crypto-currency feature for distributed and transparent transactions for EV services with higher privacy protection [117]. Second, artificial intelligence (AI)enabled system decision management with advanced EV scheduling and operation cycle handling [118]. Third, the internet of things (IoT) for accurate sensing, measurement, and seamless communication among wearable electronic devices, mobile devices, charge scheduling, and EV internal decision-making platforms [119]. All three concepts exploit rapid data transfers and operate on sensitive user data and real-time events [120]. Therefore, using advanced and secure data transfer with zero tolerance for cyber vulnerabilities is a key requirement and a vital challenge in employing the internet of vehicles and V2G operation [121,122].

A strictly managed and secured communication bandwidth is required to ensure reliable communications. During the communication setup, information about vehicle types, owner's license number and whereabouts, charging/discharging routine, charging station information, and location must be kept as confidential as possible. Moreover, in V2G, very fast (~milliseconds) recognition of the nearest and neighboring charging infrastructure and EVs and then setting up the communication link is crucial. As such, WiFi has become an obsolete technology due to security concerns, high latency, and limited spectrum. In the data-sharing stage of V2G, privacy becomes a more crucial issue. Data transfer between the EVs and entities related to user identity, server information, billing transaction, control protocols, and local aggregator need to be secured via the use of transport layer security (TLS) and unilateral authentication on the server-side, as proposed by IEC 15118-2 [123]. However, unilateral authentication (UA) often suffers from impersonation and redirection attacks as all the end LAGs and servers are hardly trustworthy. As a result, mutual authentication, concerning both server and vehicle sides, has become an additional feature to screen the shortcoming of the UA.

Cyber security is also a significant concern in the V2G scheme. The linked grid and vehicle infrastructure stand vulnerable to malware and cyber penetration. The resilience of the V2G architecture is jeopardized through physically tempering the vehicle supply equipment, insertion of malicious scripts, alteration of real-time connected load profile, and maloperation of the bidirectional power flow management. The dynamic entity of the scheme-the vehicles-often unintentionally help fast-spreading cyber assaults, especially worms and viruses, across the whole network. Such assaults could result in unprecedented consequences, involving massive blackouts, faulty switchgear operation, and unnecessary disruptions of the independent system operator (ISO) or regional transmission organization (RTO). Interconnected V2G, composed of ubiquitous connections, increases the vulnerabilities within a short time. Malware-penetrated supply equipment may compromise connected EVs, which may travel to other supply equipment and associated EVs via the interconnected system. Essential grid equipment such as the phasor management units, system analysis and monitoring units, smart metering infrastructure, protective devices, and operation could be readily compromised, and destruction may proceed due to cyber hacking and penetration.

An assault scenario is simulated by replacing an EV unit with a malicious load that ignores the demand-response protocols and control commands regarding load disconnection/curtailment [124]. When a more malicious load is inserted, maloperation of the power system follows, which triggers the operation of switchgear components. A similar mismatch between the controller units and malicious system in the V2G scheme from parasites/worms is also being studied in the current literature. In such cases, devastating malfunction of the utility and tremendous economic loss, as well as confidential information divulgement are observed [125–128].

5. Proposed Solution to Address the V2G Effect

5.1. Proper Grid Load Dispatch with V2G

Unscheduled and random addition of EV fleets affects the power quality of the utility grid in terms of real power, reactive power, power factor, and harmonics component. Thus, controlling the EV integration and energy flow in the V2G scheme is necessary. In [129], it is discovered that the utilization of fast-charging EV infrastructure reduces the steady-state voltage stability of the power grid. In V2G, efficient smart energy metering and real-time communication are required to schedule the EV fleet and gather information on the extraneous load demand of the distribution grid. In [130], a time of use (TOU) scheme is proposed to properly maintain the EV loading during the off-peak period, reducing the impact on the power-generating units. A TOU could also be devised for the EV discharging scheme. Moreover, the load variation needs to be revised, and a tentative load curve needs to be generated.

An important aspect is correctly predicting the EVs' schedulable capacity for a better economy. In [131], a novel rolling prediction–decision framework with deep long short-term memory (LSTM) procedures is proposed that shaves the load peak by nearly 30%. Moreover, during a random charging scenario, the margin of the grid power level is boosted by more than 35%, thus, making the V2G operation more resilient and economically

feasible. Furthermore, during V2G/G2V implementation, a coordination model could be dispatched to efficiently control the onboard BESS to accommodate load-leveling during discharging/charging run.

In V2G operation, centralized or decentralized control is considered with active or passive management. In a centralized control strategy, an aggregator operator (AO) takes the central charge of acquiring data from the connected EVs across the network and dispatches the required control signals to manage bi-directional power flow between UG and EV. The AO schedules each connected EV according to the load demand and generation and optimizes the energy loading/unloading respective to the vehicles' battery capacity and charging/discharging routine [132]. The AO acts as the central controller and is responsible for planning, setting, and tuning the electricity prices in V2G via an intelligent metering infrastructure at the charging infrastructure. Centralized controlling prevents user-defined control practices and only schedules the V2G operation as deemed necessary by the AO [133]. However, the user's input regarding the time of V2G operation and controlling the charging/discharging process is retained at decentralized control. Decentralized control considers the EV fleet as distributed renewable resources that are intermittent. Similar to the DERs, the EV fleet could be scheduled to maintain grid stability, especially at the LV/MV grid. External data regarding the energy flow, energy price, and co-ordinating control with neighboring EV units are also embedded in decentralized control. The droop control method and optimization control method are two mostly used decentralized control strategies.

Power transfer between EV and UG could be operated in three basic modes: V2G mode requiring intelligent multi-mode control; stand-alone mode requiring parallel control mode, and seamless transfer between the stand-alone and V2G mode requiring voltage-current double-loop control [132]. Figure 20 demonstrates the control management techniques with flexible services and value streams to initiate a smooth integration of the EV battery with the power grid for successful V2G integration. The passive management technique initiates the V2G integration, and active management comes into play during the bi-directional and unidirectional power flow. The higher the connected EV intensity, the lower the flexibility in EV scheduling. This is because curtailing a large EV fleet could lead to voltage and frequency oscillation in the power grid, disrupting the system's stability and resulting in an inefficient load control strategy. The energy transfer unit needs to be extracted from smart and aggregated charging infrastructures. Efficient active and passive energy management results in electric peak load shaving, frequency regulation, renewables offtake, and other arbitrage opportunities [133].



Figure 20. Structure for an efficient vehicle-to-grid scheme management and smooth integration [134].

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Recent research considers algorithms to determine the efficient EV scheduling strategy that can benefit both the EV user and the power companies. Consideration of the state of charge of batteries, the mode of EV charging, connecting and disconnecting period of the EV fleet to the grid, and the peak and off-peak periods of UG all play an essential role. In [135], a mixed-integer linear programming algorithm is proposed to route and schedule EVs to charge/discharge, thus allowing users to decide when and where the EV fleet needs to schedule. Moreover, the dynamic peak and valley searching algorithm is sometimes considered to reduce the energy cost and impact on the public grid by proper EV charging/discharging [136]. According to [137], the shift-working V2G model could reduce load-behavior randomness and stabilizes battery capacity for corporate energy systems (CES). The proposed system drastically improves the load-tracking capability of the CES and reduces the electrical energy price.

Depending on the connected and expected loads, the EV fleet could be scheduled to use the vehicle-to-grid power transfer at peak hours. The large magnitude of power injection to the grid results in overvoltage and variable voltage across the power distribution line. Thus, an efficient power control unit and stabilizing voltage system could be incorporated to take input from the EV battery and to provide stabilized power at grid frequency, phase sequence, and voltage. The EV unit should be appropriately covered with protective devices, significantly when the grid is damaged by lightning discharge, short circuits, under-voltage, and very low- or high-power factors. To stabilize the utility grid parameters, the right moments of energy exchange between the EV and grid could be communicated by using an energy management unit (EMU) of the plug-in charging stations, which is composed of multiport power converter units [138].

With a bidirectional charge connector, during the V2G power transfer, it is essential to use a power electronics inverter of 1-phase and 3-phase for 1-phase and 3-phase connectors, respectively. Typically, the 3-phase charger could charge more than 20 kW, whereas the 1-phase charge operates near the 8 kW range. In the V2G technique, the DC voltage from the battery DC bus goes from DC to the AC inverter unit through a power flow controller. The 1-phase output from the EV connector is passed through a variable frequency drive circuit or a phase converter to change into 3-phase power. The 3-phase voltage after grid synchronization is fed to the grid. Usually, voltage source inverters (VSIs) are employed to properly regulate system voltage and frequency, disregarding the grid's requisites. A defined voltage output from the power converter stage is obtained by using the pulse width modulation (PWM) technique to operate self-commutated insulated gate bipolar transistors (IGBTs), which work as voltage source converters (VSCs). Due to this, the converter stage could behave as a rectifier during G2V (charging) and as an inverter during V2G (discharging). An intelligent metering unit observes the bidirectional power flow, current, voltage, and frequency and calculates the credit or debit value. Harmonics reducers are added to discard odd harmonics from the system. In addition, a real or reactive power control unit could be incorporated into the system to control power factors and losses.

Different research methods involving case studies devised ways to control power quality in the V2G scenario. Table 6 summarizes the recent works in the V2G scheme with relevant goals, methodology, and outcomes.

Category	Broader Description	Issue Tried to Address	Methods Used	Outcomes	Year	Refs.
Prospects of V2G	Prospects of V2G technology from grid utility, vehicle user, and EV manufacturer	- trend and current profile of EV, battery storage, charge control mechanism, challenges, techno-economic,	 recent literature review market potential analysis of V2G technological innovation and limitation 	 the sales of EVs is improving sharply in recent years V2G is a growing field and a profitable market V2G provides ancillary services, load shaving, space for grid parameter stabilization, power factor improvement, and use as secondary battery storage government incentives help directly in the vast adoption of V2G proper battery storage technology and a time-of-use pricing scheme is required to benefit the user need structured policies for V2G implementation compared to V2G at peak hour, V2H provides more economic benefit (~ 12%) for the household consumer V2G allows a higher degree of intermittent renewable energy sources high initial cost of BEVs, battery storage, and PHEVs is one of the core issues of EV, V2G implementation newer technical features in bidirectional power flow control and net metering policies are required 	2022 2018 2016 2005 2008 2009 2018	[43] [97] [139] [140] [141] [142] [143]
	perspective	techno-political concerns, state-of- the-art practices	- bivariate statistical and hierarchical regression analysis of the survey	 perceptions and attitudes toward EV ownership and V2G plan directly depend on the income; in Northern Europe V2G is only suitable for city or suburban areas political belief is also an essential factor in V2G adoption 	2019	[18]

Table 6. Summary of recent research on V2G technology.

Category	Broader Description	Issue Tried to Address	Methods Used	Outcomes		Refs.
			- ethical, justice, or moral concerns on the V2G scheme by representing lenses of justice practices	 EV can erode distributive justice, procedural justice, cosmopolitan justice, and recognition justice V2G promotes concern regarding privacy breaching, hacking, and cyberterrorism policy measures are attached to address many of these concerns 	2019	[27]
			- V2G with second-generation EV, electrochemical- based battery model	- V2G is achievable even at 40% battery capacity	2020	[144]
			 survey on user inclination to energy generation mix in V2G scheme 	 driver prefers BEVs and PHEVs more than other EV variants generation mix > 55% results in profit from user-end renewable-focused V2G generation only slightly reduces ICE use 	2020	[145]
		- high manufacturing cost and low thermal stability of Li-ion batteries	- introduction of modular/scalable battery thermal management system (TMS)	 at ambient temperature = 35 °C: heat dissipation is independent of battery thickness and nominal capacity at ambient temperature > 35 °C: a thick battery dissipates faster at ambient temperature < 35 °C: thin battery dissipates faster mass production is feasible, so cost becomes lower 	2019	[146]
Battery storage system for V2G	Rating, durability, and proper end-of-life investigation of EV onboard battery storage systems	- battery-drain characteristics while providing V2G services	 consideration of the trip behavior and standard EV and HEV driving cycle in the UK, opportunistic V2G scheme 	 battery degradation mostly depends on power train energy throughput (EV and HEV) battery degradation is mainly sensitive to charging regime (EV) or battery capacity (HEV) requires multiple battery replacements for an entire EV lifetime 	2013	[147]

V2G services

Category	Broader Description	Issue Tried to Address	Methods Used	Outcomes	Year	Refs.
		-	standard USA-based BESS, EV, and HEV systems with shallow and deep V2G frequency drives	 V2G power transfer calculated from regulation signals battery storage cost for the deep cycle is higher than shallow cycle, and thus low profit with deep cycle drive V2G profits far exceed the battery cost during shallow/deep drives 	2012	[148]
		- proposing effective battery storage with a -	literature review	 development, design, testing, and working characteristics of different battery storage topologies for EV, HEV, and PHEV 	2020 2013	[149] [37]
		higher lifetime, lower cost, and improved charge density		 fundamental requirements and challenges of BESS for EVs in terms of energy density, cost, fast charging and power capability, lifespan, safety, and ambient-dependent performance 	2020	[150]
				 a cradle-to-grave analysis of the battery storage technologies from economic, environmental, and futuristic EV schemes (V2G, V2H) perspectives prospects of bio-inspired biobatteries for energy production 	2015	[151]
	Required control algorithms, converters,	Required control orithms, converters, and charging rastructure features - effective charge r cost-effective V2G controlling methods operation for load optimization	novel multi-objective approach applied on fuzzy logic-based predictive control strategy, IEEE 123 feeder	- optimization results in effective power load tuning towards a target value along with proper battery charger capacitance size estimation at different loads	2017	[152]
Charger, charge control and charging infrastructure for V2G	rol and charging infrastructure features G for cost-effective V2G operation		fuzzy logic based on voltage-oriented controlling on a nine-phase electric machine	 fuzzy controller controls the DC bus voltage constant CC/CV control utilizes different charging/discharging levels and enables effective three-phase fast charging with THD < 3% with very low ripple stress 	2020	[153]

Category	Broader Description	Issue Tried to Address	Methods Used	Outcomes	Year	Refs.
			 ZVS technique for charger control constant current-constant voltage control scheme is used 	 CC/CV control utilizes different charging/discharging levels duty cycle and phase-shift angle control the charger efficiency over wide power handling capacity 	2014	[154]
			 misalignment tolerant control for a wireless charger in series-series compensating system 	- improvement of wireless power transfer efficiency from 5% (at 0 cm) to 23% (at 8 cm) at cm range misalignment	2019	[155]
		- cost-benefit investigation of the optimal charge controlling	- mixed-integer linear programming technique for charge control, Monte Carlo simulation for EV charging demand and state of charge	- V2G effectively reduces the charging cost of EV	2020	[156]
		- charging and discharging strategy for economic benefit	 using the Markov framework and learning algorithm to find the most beneficial V2G schedule for consumer use of a cyber insurance scheme 	 cyber insurance scheme reduces cyber risks and information unavailability and helps to maximize consumer profit dependency on wired/wireless communication lines between the utility and charging infrastructure is reduced, and the cyber insurance company works as the buffer layer 	2017	[74]
		- AC/DC converter design for V2G	- feedforward decoupling of grid voltage, PI control strategy with a d-q model of AC/DC converter	 proposed converter control technique results in ~0.98 power factor, <5% THD, >85% efficiency 	2020	[157]

Category	Broader Description	Issue Tried to Address	Methods U	sed	Outcomes		Refs.
		- performance of single-phase bidirec- tional converter	- active neutral-point- clamped five-level converter, proportional- resonant compensator controls		proposed technique improves voltage balancing across split-capacitors, reduces power losses, and increases power quality with high converter efficiency the switching stress is reduced	2022	[158]
		- prospects and challenges in EV chargers design, control, and charg- ing infrastructure	- literature re	- - - - -	in-depth analysis of challenges and topologies of unidirectional and bidirectional chargers for successful V2G implementation unidirectional charging faces interconnection complexity and hardware availability battery charger components, filters, converters, and DC control mechanisms are reviewed AC/DC and DC/DC converters provide bidirectional power flow bidirectional charging is most suitable for V2G	2018	[76]
			- PHEV as ar filter, renew integration (feedforwar compensati model, harr lution inves	active able - d, active ng), p-q nonic pol- tigation	constant output even with renewable, reduced harmonics, smoothing power, improved dynamic stability, harmonics current compensation, reactive power control, voltage flicker reduction, reduced frequency imbalance	2011 2012 2014	[159–161] [162] [163]
Impact of V2G on the electric grid	Energy management and grid stability controlling using the V2G system	- effective EV load scheduling to maintain grid stability, frequency regulation, and facilitating renewables-based smart grid and microgrid system	- power qual characteriza assessment Nissan Leaf	ty - tion and with	V2G operation is feasible at nominal power change relative power from 85% to 10%, total harmonic distortion improves from 4.6% to 33% in discharging mode and 3.1% to 19% in charging mode	2021	[83]
			- novel DC-li PFC control with a close control syst	nk-fed strategy - d-loop em	smaller size for the proposed converter stage with medium frequency power transformer, improved power quality	2020	[164]

Category	Broader Description	Issue Tried to Address	Methods Used	Outcomes	Year	Refs.
			- non-linear controller-based partial linearized feedback on EV internal dynamics	 controllable real and reactive power injection to the grid stable V2G internal dynamics with higher power quality 	2014	[165]
			 power converters embedded with model predictive control algorithms, discrete switching states 	- agile-dynamic property with dynamic power exchange, reduced harmonics, and improved dynamic power quality	2020	[166]
			- single-phase five-level neutral-clamped converter, split control strategy for EV charger	- balance voltage at the DC-link capacitors, higher efficiency, and power quality, reduces frequency imbalance	2021	[167]
			- single-phase bi-directional EV charger topology with PV source	 V2G augments the low generation limit of PV and increases system reliability with active power injection in renewables intermittency 	2013	[168]
			- dynamic rolling prediction, deep long short-term memory algorithm, prediction-decision framework for V2G scheduling	- significant improvement in grid efficiency and resiliency	2020	[131]

Category	Broader Description	Issue Tried to Address	ldress Methods Used			Outcomes	Year	Refs.
The b Business structures in and policies for V2G c pol	The required sustainable business model for effective V2G implementation and associated change/creation of policies and regulatory steps	- stakeholder types or business markets potential with the V2G technique	- qualita intervi Europe stakeho percep V2G bu literatu icy rece	tive research ews across five ean countries, older tions of the usiness model, ure review, pol- ommendation	-	the business model is clustered into five primary categories, and more than 12 business stakeholders' option is realized policy requirements for a compelling business model and the implication of those policies mobility patterns and emerging regulations could impact the V2G market structure V2G holds substantial potential as a prominent business case	2020	[169]
		- potential revenue	- time-o: on-pea and mi at varie discha	f-use tariff in k, off-peak, id-peak is used ous power rge levels	- -	revenue increases with higher penetration of EV average battery capacity is highest (lowest) at 50% (25%) penetration changing the penetration ratio from 0.25 to 0.5 increases revenue by ~180%	2015	[170]
			margin in V2G at different EV penetration	- peak sl - cost-be	having strategy enefit analysis	-	profit increases when BESS is cheaper, and the peak tariff is almost triple the valley tariff	2020
		-	- multi-a compe game t profita pricing	aggregator tition based on heory for the ble ; mechanism	-	proposed game theory provides win-win-win cooperation among the EV user-aggregators-grid resulted in pricing benefits for both the aggregator and EV user	2019	[172]

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Category	Broader Description	Issue Tried to Address	Methods Used	Outcomes	Year	Refs.
			- role-dependent privacy preservation scheme (ROPS)	 secure interactions between vehicle and utility grid in the V2G scheme authentication methods only focused on EVs and CSs are inadequate 	2014	[173]
Cyber-attacks and	Cyber Confidentiality, privacy, and network	er Confidentiality, acy, and network rity breaches and equired action - - possible cybercrimes and assaults scenario investigation - a required safety - measure to prevent a cyber breach	- cyber insurance-based model with Markov decision process framework	 unavailability of essential information for profitable V2G practice is reduced, and cyber security improved 	2017	[74]
vulnerabilities	security breaches and required action		- energy trading via blockchain, contract theory, and edge computing	 secure and efficient V2G energy trading by improving the decision-making process of EVs to address demand-supply mismatch 	2020 2021	[174] [175]
			- privacy-aware authentication scheme using a physical unclonable function (PUF)	 proposed scheme outperforms the state-of-the-art confidentiality of user and infrastructure information and secure communication between the grid, charging stations, and utility are ensured. 	2020	[126]

5.2. System Harmonics Preservation

Another fundamental hurdle in implementing an EV or V2G technology is the harmonics distortion coming from the power converter stages of the charger and onboard diver circuitries [176]. Power quality degradation by harmonics pollution becomes more visible when the grid supplies current at high load demand (~18-24 kWh). The magnitude and phase angle of the harmonics current and voltages are usually measured to quantify harmonics demonstrating parameters such as total harmonic distortion (THD) and total demand distortion (TDD). It is reported that the third harmonics contribute around 50% of current harmonics and its magnitude directly depends on the charger circuit inductance; the lower the inductance, the worse the harmonics profile [177]. During the planning of V2G, both the TDD and THD parameters must be maintained within the standard limit of IEEE 519 (5% and 5%) and IEC 61,000 (5% and 3%) standards. TDD considers the fundamental line current, whereas THD considers the maximum line current to evaluate the total harmonics level. According to [176], TDD assesses the harmonics profile with better accuracy than THD. In [153], a nine-phase converter with three isolated neutral-based ninephase EVs and an onboard battery charger (OBC) is embedded with fuzzed logic-based voltage-oriented control (VOC) algorithm to effectively maintain the voltage and current levels at both the grid side and battery side during V2G admission. The combinations show an excellent reduction of THD from the power grid parameters and ripple stresses on the battery pack.

Apart from the grid harmonics, during the run, the stator end of the EV motor could demonstrate lower and higher order MMF harmonics, which increases the rotor circuit eddy current loss. In interior permanent magnet machines (IPMs), the stator magnetomotive force (MMF) space harmonics produce a high iron loss in the rotor and magnet parts. It is reported that utilizing multiple three-phase winding in a nine-phase 18-slot 14-pole IPMs could cancel out almost all the subharmonics and a portion of higher-order harmonics [178]. For permanent magnet synchronous machines (PMSMs), using six-phase windings arranged in two three-phase slots can completely discard the notorious fifth harmonics [179]. Researchers are currently considering waiving distinct winding configurations, pole numbers, slot, and fractional slot/phase arrangements to eliminate the third, fifth, and other odd space harmonics and to reduce all higher-order harmonics. This fractional-slot per phase strategy could be feasibly used for EVs housed with IPMs, PMSMs, synchronous reluctance machines (SRMs), and synchronous wound field machines (SWFMs) [180–182].

5.3. Battery Energy Storage Handling

During bidirectional power flow between the vehicle and grid, the charging and discharge cycle of the EV need to be maintained adequately lest the battery lifetime and capacity level degrade. Long-time operation of V2G with higher battery capacity raises the depth of battery discharge and stresses the powertrain [147]. In Figure 21, the power rating and discharge level are associated with various battery storage systems and their relevant application features [94]. It is estimated that by 2022, China should continue its colossal leadership in battery storage manufacturing, with nearly 70% of the all-battery storage for EVs being made within its borders.

In the V2G technique, multi-object optimization algorithms are often considered to properly schedule the EV fleet to reduce battery degradation and make the system more economical. The most common raw materials used for EV battery manufacturing include but are not limited to lithium, nickel, cobalt, copper, and graphite. In 2011, it was concluded that both Lead-acid and NiMH battery-based BEVs are uneconomical to implement in V2G techniques [183].



Figure 21. Battery energy storage rating and discharge time for various applications [89].

In [144], the battery life cycle of an EV is analyzed by examining the battery capacity to provide the necessary torque to run EV wheels and to provide adequate power back to the distribution grid during the V2G technique. In second-generation EVs, launched in 2016 with 60 kWh of Li-ion battery storage, the battery state of health (SOH) needs to be above ~75% to sufficiently run the EV. Such batteries could back nearly 350 to 500 km drive range for nearly 14–20 years. Furthermore, during V2G, intermediate storage could sufficiently bring the load demand of the power grid if it could only stay at 25% of the entire storage limit [184]. Thus, second-generation EV batteries are well aligned with the EV drive and V2G implementation with the overall EV lifetime and would seldom require replacement.

Usually, the lithium-ion battery lifetime model estimates the battery degradation level in terms of temperature rise, uncontrolled state of charge (SoC), unscheduled battery discharge/charge cycle, and depth of discharge (DoD). Moreover, the lifetime model could be extended to estimate the associated increase in EV charging and energy/power fade. The national renewable energy lab (NREL) has developed a detailed battery lifetime model that is often considered for standard comparison. In [185], an empirical capacitor fade model, backed by an electrothermal model, is proposed and validated in an experiment against LFP/C and NCA/C Li-ion cells to encumber calendar and cycle effects. It is obtained that, at light V2G, NCA/C deteriorates faster than LFP/C. Furthermore, advanced switching algorithms could be exploited during battery discharge to engage a subset of the battery pack to a defined current demand and modulate each battery's electrochemical operation for proper current extraction [186].

The charging cycle alters the battery's internal resistance and exacerbates the capacity fade rate. The housed battery pack comes with a predefined optimal level of charging and a discharging current limit that needs to be maintained in every operation, lest negative effect follows. The injection (extraction) of high peak currents from the EV batteries during G2V (V2G) power flow also degrades the battery lifetime. In [187], it was reported that the optimized charging control makes the battery last longer for a regular EV run compared to other typical charging methods.

Proper heating, ventilation, air conditioning (HVAC) control, and BMS improve EVs' battery lifetime and driving range. On average, by improving the ventilator system and incorporating the climate control methodology of HVAC, battery life could be increased by 14% while curtailing EV power consumption by 39% [188,189]. The vehicle's temperature also impacts the battery life, similarly to the depth of discharge (DoD). A fuzzy logic-based EV thermal management control system (EVTMCS) could sustain cabin and battery temperature's thermal comfort and reduce battery lifetime cost by ~3% [190].

High-frequency and low-frequency currents need to be supplied during the motor run. High-frequency current peak results in fast battery degradation. In [191], a hybrid energy storage system (HESS) is proposed, composed of ultracapacitors (Ucs) and Liion batteries. The authors incorporated a field-programmable gate array (FPGA) based controlled interleaved bidirectional buck-boost converter that monitors energy transfer between the Ucs and batteries. Moreover, FPGA provides the required gate signal to the converter stages to shave the battery current overshoots. The battery supplies the lowfrequency current in such a composition, and the high-frequency current comes from Ucs.

5.4. Communication System and Cyber Vulnerabilities

Dynamic charging/discharging in V2G requires a speedy and efficient control strategy, a communication system to secure economic benefits, and the transfer of information across the power grid, EV supply equipment, charging infrastructure, and end-users. Unique to other architectures, the information transferred through the V2G network directly influences physical power grid equipment's control strategy and scheduling. Thus, any breach throughout the layer could damage power infrastructure and burden the system with larger losses. The IEEE 802.11p and IEEE 1609 protocols comprise the fundamental layers for fast and secure communication in dynamic vehicular environments [192]. In addition, a dedicated short-range communication (DSRC) protocol could be implemented for V2G, V2V, and V2I systems. In V2G, DSRC could retain fast network acquisition and signal authentication and could sustain effective data transfer between the grid and power grid entity at high vehicular movement (>500 km/h), even at non-line-of-sight communication [193]. Furthermore, immunity against harsh weather conditions and interoperability at low latency make DSRC a highly reliable protocol for V2G realization.

Protection against cyber penetration and threats associated with blockchain, AI, and IoT connectivity, is a must-need for the V2G system. The connection between the EVs, EVCS, and UG should be maintained to ensure the confidentiality of user information, charging/discharging routine, information on connected and in-use services, and others. Dispatching a mutual, reciprocal authentication technique is one of the prevalent solutions to curtail cyber security concerns, especially network redirection and impersonation attacks. The connected EVs to the aggregator must be registered and checked for authenticity before initiating the charging/discharging maneuver. Physical unclonable functions (PUF) could be employed in integrating secure user key-exchange authentication (SUKA) protocols [194]. Under this framework, the vehicle information and users' whereabouts are coded into pseudo-identity, screen identity theft, and divulge confidential information. The EVs and aggregators could be designed with unique identification secret keys that filter out any malicious data flow across the network. The current trend of blockchain, AI, and cryptographic procedures may also help reduce communication overhead, improve efficient energy management, and be lightweight. The presence of cyber worms and viruses could be encircled by properly dispatching mixed-integer linear programming (MILP) protocols [195]. An infected single EV unit could spread the worms to other EVCSs. A danger level model could be considered to enumerate the worm propagation across the network, and a defense mechanism could then detect malicious variables using a defense mechanism.

6. Conclusions

This review details the vehicle's current scenario and future outlook on grid (V2G) technology. The technical challenges are presented, structured, and detailed with possible solutions by reviewing the literature's research works, reports, and theoretical presentations. The work starts with a brief overview of the present EV culture, V2G trend, and separate policies and measures of successful V2G implementation for the investors and stakeholders. Then, the basic information regarding EVs and associated infrastructure are revised. Next, the V2G technique is introduced, followed by the impacts of V2G on the current electrical infrastructures. Finally, the challenges associated with V2G practices and their possible

solutions are detailed. During the research on V2G culture implementation, the following points are observed:

- At present, EVs' growth is tremendous, leading to a vast opportunity to rationalize V2G technology.
- V2G stands promising to provide ancillary services, such as load shaving, reactive power flow control, system voltage, and frequency fluctuation reduction.
- Among the challenges of V2G implementation, the most crucial part is related to the battery life cycle. A higher magnitude of the charging/discharging cycle of the battery could lead to premature degradation of batteries and reduces the EV drive range.
- Power loss in the power electronics conversation stages and associated harmonics could disturb the grid stability and, thus, needs proper controlling.
- At present, V2G is still immature to marketize. Moreover, there is a lack of a proper business model to commercialize the V2G scheme.
- The current electrical grid, associated electrical machinery, and control strategies need to be revised to check their compatibility to withstand large EV penetration.
- Countries have already begun revising the EV charger standards to enjoy bidirectional power flow. Moreover, top-tier EV manufacturing farms have joined across the border to initiate proper business models and technological maturity for V2G implementation.

During the analysis, it was observed that though the V2G market is still growing at present, it holds significant promise for future grid modernization and incorporating distributed renewable energy sources. Moreover, through efficient net energy metering policies, V2G could benefit both the EV user and power retailers. It is also found that current literature is lacking in devising a proper V2G model. The per unit cost of EV needs to be reduced while the battery density needs further improvement. In conclusion, the authors suggest further research should focus more on an efficient business model for V2G and proper energy management between the grid and batteries to boost the economy of the scheme while preserving the EV battery lifetime.

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Nomenclature

EV	Electric Vehicle	DSRC	Dedicated Short Range Communication
V2G	Vehicle-to-Grid	SUKA	Secure User Key-exchange Authentication
PV	Photovoltaic	RBO	Regenerative Braking Operation
BEV	Battery Electric Vehicle	EVCS	Electric Vehicle Charging Station
CPS	Cyber Physical System	LCV	Low Commercial Vehicle
SEV	Solar Electric Vehicle	HRS	Hydrogen Refueling Station
PEV	Plug-in Electric Vehicle	IEA	International Energy Agency
V2V	Vehicle-to-Vehicle	REEV	Range Extended Electric Vehicle
V2H	Vehicle-to-Home	EVSE	Electric Vehicle Supply Equipment
V2G	Vehicle-to-Grid	FPGA	Field Programmable Gate Array
CEM	Clean Energy Ministerial	CARB	California Air Resources Board
R&D	Research and Development	WEVCS	Wireless Electric Vehicle Charging Station
EDF	Électricité de France	IWCS	Inductive Wireless Charging Station
WTW	Well to Wheel	CWCS	Capacitive Wireless Charging Station
OBC	Onboard Charger	PMWCS	Permanent Magnet-gear Wireless Charging Station
BMS	Battery Management System	RIWCS	Resonant Inductive Wireless Charging Station
RPM	Revolution per Minute	IRENA	International Renewable Energy Agency
WTT	Well to Tank	ICE	Internal Combustion Engines
FCEV	Fuel Cell Electric Vehicle	MILF	Mixed Integer Linear Programming
PCC	Point of Common Coupling	HEMS	Home Energy Management System
EVM	Electric Vehicle Management	STATCOM	Static Synchronous Compensator
EMS	Energy Management System	DER	Distributed Energy Resource
APF	Active Power Filter	ISO	Independent System Operator
AI	Artificial Intelligence	TLS	Transport Layer Security
IoT	Internet of Things	UA	Unilateral Authentication
ZEV	Zero Emission Vehicle	RTO	Regional Transmission Organization
ToU	Time of Use	LSTM	Long Short Term Memory
AO	Aggregator Operator	CES	Corporate Energy System
EMU	Energy Management Unit	PWM	Pulse Width Modulation
VSC	Voltage Source Converter	IGBT	Insulated Gate Bipolar Transistor
G2V	Grid to Vehicle	PHEV	Plug-in Hybrid Electric Vehicle
TDD	Total Demand Distortion	BESS	Battery Energy Storage System
VOC	Voltage Oriented Control	EMI	Energy Metering Infrastructure
SoC	State of Charge	PMSM	Permanent Magnet Synchronous Machine
DoD	Depth of Discharge	SRM	Synchronous Reluctance Machine
UC	Ultra-capacitor	SWFM	Synchronous Wound Field Machine
PUF	Physical Unclonable Function	NREL	National Renewable Energy Lab
THD	Total Harmonic Distortion	HVAC	Heating, Ventilation, Air Conditioning
OBC	Onboard Battery Charger	EVTMCS	Electric Vehicle Thermal Management Control System
MMF	Magnetomotive Force	HESS	Hybrid Energy Storage System

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