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Article

Electric Vehicle as a Service (EVaaS): Applications, Challenges and Enablers

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Abstract: Under vehicle-to-grid (V2G) concept, electric vehicles (EVs) can be deployed as loads to absorb excess production or as distributed energy resources to supply part of their stored energy back to the grid. This paper overviews the technologies, technical components and system requirements needed for EV deployment. Electric vehicles as a service (EVaaS) exploits V2G technology to develop a system where suitable EVs within the distribution network are chosen individually or in aggregate to exchange energy with the grid or individual customer, or both. The EVaaS framework is introduced and the interactions among EVaaS subsystems such as EV battery, charging station, load and advanced metering infrastructure is studied. The communication infrastructure and processing facilities which enable data and information exchange between EVs and the grid are reviewed. Different strategies for EV charging/discharging and their impact on the distribution grid are reviewed. Several market designs that incentivize energy trading in V2G environments are discussed. The benefits of V2G are studied from ancillary services, supporting renewables and environmental perspective. The challenges to V2G are studied from battery degradation, energy conversion losses and effects on distribution system perspective.

Keywords: Electric vehicle; vehicle-to-grid (V2G); smart grid; communication; energy trading; charging; electric vehicles as a service (EVaaS).

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1. Introduction

Due to climate change, fossil energy reserves and greenhouse gas (GHG) emission concerns, efforts are currently going towards the transition to electric mobility [1]. There exist several kinds of government policies designed to reduce GHG emissions and promote the acceptance of electric vehicles (EVs), such as the UK Vehicle Scrappage Scheme (VSS) [2], Car Allowance Rebate System (CARS) in the US [3], Zero Emission Vehicle (ZEV) programs in California, China and EU [4], and the Corporate Average Fuel Economy (CAFE) standards [5]. There are also government incentives designed to support policy-driven adoption of EVs, such as purchase rebates, tax credits, tax exemptions, and waivers on charging and parking fees. However, due social obstacles, technical limitations and cost premiums compared to conventional internal combustion engine (ICE) vehicles, EVs have not been widely adopted [6]. The main types of EVs on the market are battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEVs), extended range electric vehicle (EREVs) and fuel cell vehicles (FCVs) [7]. For purposes of the article, all electric vehicles with plug-in capabilities are collectively referred to as "EVs".

Range anxiety - fears over the distance EVs can travel between charges - is a major technological barrier to large-scale adoption of EVs [8]. One of the factors influencing range anxiety is the availability of EV charging points. Fears over lack of charging points was identified in [9] as the biggest concern with regards to EV ownership. However, with several government policies across the globe supporting the increased penetration of EVs [10], there has been a rapid rise in the number of charge points. The remaining driving range (RDR) - distance an EV can travel with the residual energy in the battery - is another factor influencing range anxiety. The RDR of EVs cannot be accurately estimated by current technologies; hence, drivers tend to reserve around 30% of battery capacity as an emergency buffer, to protect them from running out of power [11]. With accurate RDR estimation, drivers would be able to make efficient use of their limited battery capacity, thereby minimizing range anxiety considerably [12]

Known for their features as energy-conserving, revenue generator and emission free, EVs have become the future trend. EVs have advantages over ICE vehicles, most notably the ability to be used as a service for the electricity grid - electric vehicles as a service (EVaaS). EVs can provide service individually or as part of an aggregation. In the later, EVs are selected into groups by aggregators, to create a larger, more manageable generation capacity or load for the electricity grid [13]. EVs receive power from the grid to charge their batteries in grid-to-vehicle (G2V) mode, whereas in vehicle-to-grid (V2G) mode, EVs supply part of their stored energy back to the grid. We use the term "V2G" to broadly refer to both G2V (unidirectional) and V2G (bidirectional) energy flows in our article. Although the concept of V2G was introduced over two decades ago [14], it is still in the very early stages of development. There are different versions of V2G characterized by their energy exchange processes such as vehicle-to-home (V2H), vehicle-to-building (V2B) and vehicle-to-vehicle (V2V). V2H is a small-scale version of V2G which allows an EV to supply homes with the energy stored in its battery [15]. Similar to V2H, V2B allows EVs to power buildings [16], whereas V2V involves energy exchange between EVs in social hotspots such as charging stations, parking lots and swapping stations [17].

In V2G concept, EVs are integrated into the electricity grid, where energy is first stored in the EV battery and then fed back into the grid. In [18], the technical, commercial and domestic proposition of V2G technology to the distribution network is evaluated through demonstrator projects. From a utility perspective, there are numerous economic benefits from V2G. These include ancillary services such as energy balancing, voltage and frequency regulation, active and reactive power support, current harmonic filtering, spinning reserves, valley filling, peak shaving and load following. V2G can also improve the technical performance of the electricity grid in areas such as stability, reliability, efficiency and resilience. V2G can further reduce emissions, replace large-scale energy storage systems, improve load factors, provide support for renewable energy sources (RESs), and by contributing to local consumption, could reduce electricity transport losses in grids with high penetration of decentralized generation. Additionally, the savings in utility operations will minimize the overall service cost to customers, which will be reflected in energy prices. The aforementioned benefits are not specific to either G2V or V2G alone, but true of V2G in general.

While the potential benefits of V2G transition have been widely recognized, they may not accrue without significant challenges. Impediments to V2G actualisation include resistance from automotive and oil sectors, communication infrastructure needed for information exchange, battery degradation, requirements for monetization of energy losses, and technical, political, social and cultural obstacles. EV battery degradation costs happens to be one of the main barriers to V2G transition. An additional issue is that energy flow will become bidirectional and increasingly complex. Since the distribution grid has not been designed for this purpose, service capabilities of V2G devices tend to be limited. Conversely, bidirectional communications implementation in V2G infrastructures unlocks new possible vulnerabilities.

The implementation impact of V2G technologies on the distribution system and strategies for V2G interfaces for individual and aggregated EVs were studied in [19]. The study in [20] discussed the operation of EVs and their impact on grid stability. The methodology adopted for power flow under V2G scheme and challenges associated with the commercial level adoption of V2G are described in [21]. The study in [22] inspects the implementation challenges of EVs infrastructural and charging systems in conjunction with several international standards and charging codes. The ancillary service potential of V2G is presented in [23] and the potential impacts, challenges and future market penetration capabilities of V2G technology is discussed. Several studies have been conducted to evaluate the impacts of V2G integration on the utility. However, little attention has been given to maximizing the full potentials of V2G from an EV-prosumer perspective. The technologies, technical components and system requirements needed for the deployment of EVs for grid-related services are reviewed in this article. The system architecture and communication infrastructure for EV-enabled microgrids are introduced. The market design and various mechanisms that motivate EV owners to participate in energy trading are discussed. Optimization methods for EV charging/discharging, and benefits and barriers to the deployment of EVs are presented and evaluated.

2. Overview of EVaaS

2.1. EVaaS Framework

EVaaS describes a system in which heterogeneous electric vehicles communicate with the electricity grid to participate in grid-related services [24,25]. EVaaS exploits V2G technology to develop a system where suitable EVs within the distribution network are chosen individually or in aggregate to exchange energy with the grid or individual customer, or both. It provides the opportunity for EV owners to benefit from an additional revenue stream. EV owners can be incentivized to charge their EV batteries when the energy generated exceeds demand, example, too much energy being generated from RESs or off-peak hours. By contrast, EV owners who self-generate electricity from RESs or connect to the grid to charge at low-demand, cheap tariff, can then market the excess or unneeded energy stored in their EV batteries when energy costs are higher or during peak demand. Thus, EVs can act as an energy reserve for the grid. The operation of EVaaS system is a distinctive combination of EV, an energy management system and a service contract which can deliver value by providing demand response services.

EV owners can go into a contract or agreement with the utility to make charging and discharging controlled, coordinated and more predictable. The utility can offer lower energy price to incentivize EV charging and battery insurance or maintenance service to incentivize EV discharging in exchange for EV owners agreeing to charge and discharge the battery, respectively, to meet the grid requirements. Based on this approach, the implementation of a centralized charging and discharging solution becomes feasible, as well as the possibility of maximizing system efficiency. Alternatively, EV owners can voluntarily participate in EVaaS without making commitment with the utility. Different incentives can be offered by the utility to motivate the EV owners to charge or discharge their batteries, depending on the current demand and supply of the grid. The EV owners will individually consider their charging or discharging options in a distributed fashion. Based on this approach, a decentralized charging and discharging solution can achieve maximum system efficiency.

2.2. EVaaS Architecture

The architecture of an EVaaS system with interactions among subsystems is shown in Fig. 1. The EVaaS system typically consists of EVs, loads (critical and non-critical), charging stations, smart meters, power lines, communication infrastructure and microgrid control centre or aggregators [13]. The system is remotely monitored and controlled by the microgrid control centre using a supervisory control and data acquisition (SCADA) system, while the subsystems communicate with each other through a communication network to effectively carry out tasks and collectively achieve an objective. The communication network facilitates the collection of necessary data from EVaaS subsystems and allows the aggregator to efficiently optimize EV charging and discharging. However, this is dependent on status monitoring and information update of both parked and moving EVs. The information includes the current location of EV or where it will be in the next time frame, battery capacity and state of charge (SOC). Using this information, the aggregator can forecast or estimate the energy demand or supply from EVs within a specific region.

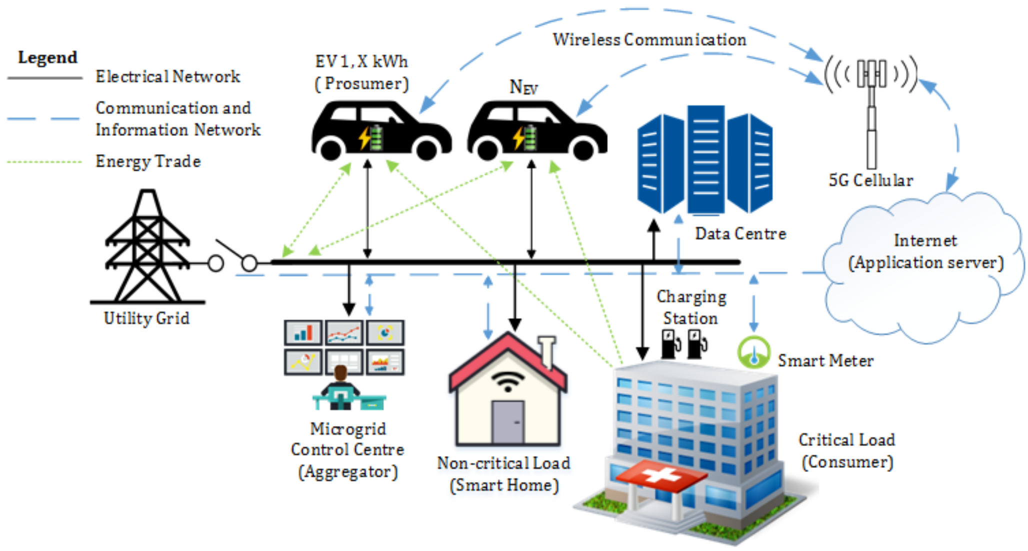


Figure 1. EVaaS system architecture.

3. System Requirements

3.1. EV Battery

While ICE vehicles get energy from burning fossil fuel, an EV is powered from a battery. Unlike the batteries used in mobile phones, laptops and other battery-powered electronic devices, EV batteries are designed to achieve prolonged running time with high power and energy capacity. Automakers have different EV passenger models, with battery capacities boasting up to 100 kWh. The study in [26] investigates larger battery capacities (200 kWh and above) for futuristic mobile usage and recommends subdividing the total battery unit into mechanically separated containers. When an EV is being charged, chemical reactions go one way and the battery absorbs power, these reactions are then reversed to produce electricity when the EV is being discharged. Some of the EV battery technologies widely deployed in the real world include lithium-ion (Li-ion), nickel-metal hydride (NiMH) and lead acid [27,28]. Among them, Li-ion is the most common battery technology. Several potential technologies that might be able to achieve better or comparable performance to Li-ion batteries are in early stage of development. These include nickel-cadmium (NiCd), sodium-sulfur (NaS), zinc bromid (Zn-Br) and aluminium-air (Al-air) [29]. The study in [30] details the expected development in battery technology by 2030. As observed in Table 1, Li-ion is currently the widely accepted battery technology in the EV market [31–43]. This can be attributed to its lightweight, high density, low self-discharge rate and prolonged life features. The risk of explosion from overcharged cells and life cycle reduction from undercharged cells are the disadvantages associated with Li-ion batteries.

The lifespan of the Li-ion batteries are typically estimated through calendar life and cycle life. The calendar life is the retainable duration in terms of calendar years, independent of charge and discharge cycling [44]. The cycle life estimates the capacity retention during continuous charge and discharge cycling before degrading significantly [45]. To predict battery life, study its behaviour and simulate its performance under dynamic conditions, a battery model is required. The types of battery models widely studied include electrochemical, experimental, mathematical and electric circuit models. The most accurate is the electrochemical models, however they require in-depth knowledge of the chemical reactions of batteries and complex set of equations that govern battery behaviour [46,47]. Experimental models are based on experimentation to determine parameters associated with battery behaviour [48,49]. Mathematical models consist of stochastic approaches that capture battery behaviour [50,51]. Electric circuit models provide an equivalent representation of battery characteristics. The basic equivalent circuit model consists of an open-circuit

Table 1. Overview of different EV passenger models considering battery technology, capacity and charge times.

EV Model	Battery Technology	Capacity	Charge Times
Nissan Leaf e+ Tekna [31]	Li-ion	59 kWh	100% charge in 11.5 hrs on 6.6 kW AC 80% charge in 1.5 hrs on 50 kW DC
BMW i4 [32]	Li-ion	80.7 kWh	100% charge in 8.25 hrs on 11 kW AC 80% charge in 31 mins on 205 kW DC
Audi e-tron [33]	Li-ion	86 kWh	100% charge in 9.25 hrs on 11 kW AC 80% charge in 30 mins on 150 kW DC
Chevrolet Bolt [34]	Li-ion	66 kWh	100% charge in 10 hrs on 7.2 kW AC 80% charge in 1 hr on 50 kW DC
Hyundai Ioniq Electric [35]	Li-ion Polymer	38.3 kWh	100% charge in 6 hrs on 7.2 kW AC 80% charge in 57 mins on 50 kW DC
Volkswagen e-Golf [36]	Li-ion	35.8 kWh	100% charge in 5.15 hrs on 7.2 kW AC 80% charge in 45 mins on 50 kW DC
Mercedes-Benz EQC [37]	Li-ion	80 kWh	100% charge in 8 hrs on 11 kW AC 80% charge in 40 mins on 110 kW DC
Kia e-Soul [38]	Li-ion Polymer	64 kWh	100% charge in 9.35 hrs on 7.2 kW AC 80% charge in 54 mins on 100 kW DC
Jaguar I-Place [39]	Li-ion	90 kWh	100% charge in 12.7 hrs on 7 kW AC 80% charge in 40 mins on 100 kW DC
Tesla S [40]	Li-ion	100 kWh	100% charge in 9 hrs on 10 kW AC 80% charge in 30 mins on 150 kW DC
Renault Zoe [41]	Li-ion	52 kWh	100% charge in 9.25 hrs on 7 kW AC 80% charge in 1 hr on 50 kW DC
Peugeot e-208 [42]	Li-ion	50 kWh	100% charge in 7.5 hrs on 7 kW AC 80% charge in 30 mins on 100 kW DC
Vauxhall Corsa-e [43]	Li-ion	50 kWh	100% charge in 7.5 hrs on 7.4 kW AC 80% charge in 30 mins on 100 kW DC

voltage in series with a resistance and a parallel combination of resistance and capacitance [52–54].

3.2. EV Charging Station

An EV charging station, also called charge/charging point, electric recharging point and electric vehicle supply equipment (EVSE), is an equipment that connects an EV to the electricity grid. When EVs are plugged into a charge point, they can behave as loads or generators to the electricity grid. The rapid growth in the global EV market has led to the proliferation of charger designs, charging strategies, charging techniques and charging networks. Techniques for charging and discharging of EVs, with emphasis on convenience, simplicity, flexibility, and high efficiency, have become the motivation of current research in academic and industrial communities [55]. The two main charging solutions for EVs are conductive and inductive methods [56]. Conductive charging typically involves hard-wired connection (electrical contact) between EV and the source of electricity, or EV and load in a discharging scenario. While inductive charging works on the principle of inductive power transfer (IPT), where magnetic field is used to transfer power across an air gap to a load. Here no power cable, physical contact or human intervention is required. The exclusion of cables, relatively low maintenance and autonomy for the driver has improved their practicality in V2G systems [57]. Although there have been recent progresses in inductive methods [58,59], conductive methods remains the most common solution [60].

The time it takes to charge EV batteries is currently longer than the refuelling time of ICE vehicles to satisfy the same driving demands. EV charging rate is determined by how many kilowatts the charge point can provide and the EV can accept – the higher the power output, the faster the charge. Currently, the three main types of EV charging - representing the power outputs, and therefore charging speeds - are slow, fast, and rapid. Slow charging (level 1) can be done using existing electrical circuits. Level 1 chargers plug directly into a standard 120 volt AC outlet, and are suitable for home or office use cases due to long charging sessions. Unlike the previous case, fast charging (level 2) requires installation of residential or public charging equipment. Level 2 chargers offer charging through a 240 volt AC plug, and are largely deployed in public places such as park and ride facilities, shopping centres, car parks, airports and universities. While levels 1 and 2 charging are adequate to serve the day-to-day needs of EV owners, long-distance or unplanned trips in EVs need to be considered. Rapid charging (level 3) is available in a much higher voltage, often charge using DC and can achieve 80% of charge in about 30 minutes, depending on the capacity of the EV [20]. Level 3 chargers are often used as range extenders along major roads and in urban environment to support drivers in urgent need.

To achieve a refuelling time that is comparable to that of ICE vehicles, EVs would need charging stations with much higher power output. Extreme fast charging (XFC) is an emerging technology with potentials to address the fast charge barrier and be truly competitive to the ICE refuelling experience [61]. XFC stations should be able to support charging at 400 kW, recharge an EV in less than 10 minutes and provide up to 200 additional miles of driving [62]. However, there are still many barriers that need to be addressed towards the standardisation and successful implementation of XFC. The technology gaps in XFC topology is identified in [63]. The study in [62] investigates the XFC technology-based charging infrastructure which will be necessary to support current and future EV refueling needs.

With EV batteries becoming cheaper, automakers are equipping new model EVs with more battery capacities. What used to be considered fast charging for a 24 kWh battery is no longer fast when the battery size reaches 60 kWh or more. To address the changing market environment and meet the expectations of EV stakeholders, CHAdeMO has developed an ultra-high-power charging protocol enabling 500 kW charging and allowing for maximum current of 600 A [64]. This new DC charging standard aims to support shorter and safer charging using ultra-fast charging technology and is another step closer to achieving a refueling time that can be competitive to the ICE refuelling experience. The background and technical challenges of harmonising this new DC charging standard and its impact on the global EV charging infrastructure outlook is presented in [65]. EV charging station characteristics are presented in Table 2.

There is a growing interest in the integration of solar photovoltaic into the EV charging system. Solar-powered EV charging stations can help reduce GHG emissions, charging costs and the impact of additional load on the grid. Different technologies for solar-powered EV charging and their deployment in the real world are discussed in [66]. While solar-powered charging stations bring opportunities for EVs, the environment and the grid, the uncertainty and intermittent nature of solar power raises challenges in timely utilization. The concentration of electricity output during the daytime limits the contribution of solar power in meeting a large fraction of typical energy demand. Thus, a grid connection or battery bank is necessary to guarantee effective operation of the solar-powered charging station.

Table 2. EV charging station characteristics and charging power levels [20,22,30,55,63,64].

Types of EV Charging	Description	Typical Usage	Interface for Energy Supply	Power Capacity (kW)	Voltage (V)	Current (A)
Level 1 (Slow)	Opportunity charger (any available outlet)	Home or office base charging	Any convenient outlet	1.4 1.9	120	12 16
Level 2 (Fast)	Primary dedicated charger	Privately and publicly base charging	Electric Vehicle Supply Equipment	8 19.2	240	32 80
Level 3 (Rapid)	Commercial fast charger	Dedicated charging stations	Electric Vehicle Supply Equipment	100	200 - 500	< 200
XFC (TBD)	Extreme fast charger	Dedicated charging stations	Electric Vehicle Supply Equipment	400	800+	TBD
Ultra-high-power (Ultra-fast)	Ultra-high-power charger	Dedicated charging stations	Electric Vehicle Supply Equipment	500	1,500	600

3.3. Load

Load indicates an electrical component (device or machine) or a collection of equipment that consumes electrical energy. Based on demand response management, loads in a building can be divided into two categories - controllable and non-controllable. Non-essential loads that can be deferred or interrupted for a limited period of time with minimal effect on convenience are considered as controllable loads. These include air conditioners, water heaters, dish washers, clothes washers, clothes dryers and EVs. While loads such as lighting, cookers, microwave ovens and other plug loads are considered as non-controllable loads. Building loads in a power system can be categorized into two groups: critical and non-critical loads. Critical facilities which need to be operating during power outages such as hospitals, care homes, residential houses with life support equipment, water and communication infrastructure, control centres, data centres, evacuation centres, emergency shelters, police and fire stations, military bases and airports are considered as critical loads. Non-critical loads are not essential for human health and safety, and they would generally be loads not categorized under critical loads.

Load profile represents the pattern of energy usage of a consumer, both daily (on-peak and off-peak) and seasonally (summer and winter). Modern girds are usually known to be based on the behaviour of consumers to manage the load and supply in the distribution network, where reliable and efficient delivery of electric services are dependent on the load profile. Load forecasting is the predicting of power or energy needed to meet the short-term (up to a day), medium-term (a day up to a year) or long-term (over a year) demand. The load profile can be forecasted using techniques such as similar-day approach, time-series method, regression method, neutral networks, fuzzy logic, knowledge-based expert systems, adaptive load forecasting, iterative reweighted least-squares and exponential smoothing [67,68]. The accuracy of forecasting is of significant importance for the planning and operation of electric utilities.

3.4. Advanced Metering Infrastructure

EVaaS applications require smart sensing systems which are able to get information in real-time on power consumption and power quality measurements to support energy management applications [69]. Advanced metering infrastructure (AMI), also known as smart metering, is an essential component in the realization of the smart grid vision[70]. AMI is a configured infrastructure that integrates smart meters, data management systems and communication networks to enable two-way communication between the utility and consumer [71]. AMI provides time stamped information and establishes two-way communication between smart meter and the utility. With two-way communication, many services that were nearly impossible to implement without smart metering are now applicable. These services include power outage detection, power quality measurements and power flow monitoring. The power flow monitoring information is important as it enables the utility to react rapidly on changes in consumption levels.

Unlike traditional meters, smart meters are self-reading meters which give more detailed information on energy usage in near-real time. The smart meter stores various types of data, such as executed or received commands, event logs, time of use tariffs and the firmware. The smart meter has either an Ethernet interface to connect to wireline services or a direct interface to a wireless service. Data of the smart meter is collected and transmitted to the utility using wide area network (WAN) connection. Smart meter connections to home area network (HAN) are fundamental to residential or building management and allow appliances to respond to time-based pricing signals or other triggers carried over the grid. Key features of smart meters include load limiting and balancing for demand response applications, remote command (turn on/off) operations, power outage detection, time-based pricing, power quality monitoring (active and reactive power, phase, voltage, current and power factor) and power consumption measurement for utility and consumer.

4. EVaaS Communications

EVaaS communications enable data and information sharing among EVaaS subsystems, and it consists of communication infrastructure, such as wired and wireless networks, and processing facilities, such as data centre and cloud computing. The smart meter facilitates the transmission of data through commonly available fixed wired and wireless networks, such as Fixed Radio Frequency, Power Line Communication (PLC), Broadband over Power Line (BPL), as well as public networks such as cellular, landline and paging. Consumption data from the smart meters are received, stored and analyzed to provide useful insights to the utility. The smart meter also responds to remote command from the utility.

4.1. V2G Communications

V2G communications enable EVs and the grid to interact and exchange information. This is crucial to solve problems related to V2G management. By enabling real-time and reliable communication between EVs and the grid, energy resources distributed over large geographical areas can be managed effectively to enhance the overall system performance. The communication network in V2G systems must be bidirectional to ensure substantial information exchange [72]. The system needs information control that is aware of EV location, battery capacity, battery efficiency, SOC, energy price and transportation cost. Transmitting this information and receiving commands over efficient bidirectional communication links is an essential requirement for successful V2G integration. Wireless communication is the ideal solution for V2G systems for various reasons, most notably because EVs are mobile and cannot connect to wireline services. Wireless communication enables the simultaneous transmission of data to dispersed EVs within a wide area coverage.

Different wireless communication technologies which have been implemented for short- and long-range data communication in V2G systems include Near Field Communication [73], Bluetooth [74], Zigbee [75], IEEE 802.11p [76] and WiMAX [77]. Bluetooth and ZigBee protocols are suitable for short-range data communication, such as between EV and charging station, offering a coverage area of up to 100m, while Near Field Communication suffers from very short communication range of up to 10cm [78]. IEEE 802.11p and WiMAX technologies are the standard protocols for long-range communications. The studies in [79,80] details the IEEE 802.11p standard and mobile WiMAX (based on IEEE 802.16e standard). IEEE 802.11p technology, which offers a coverage area of up to 1km, data rates of up to 54 Mbps and latency as low as 50 ms, is the popular standard for vehicular networks. WiMAX technology, on the other hand, has similar features as IEEE 802.11p but offers longer range communication of up to 5km, higher data transfer speed of up to 100 Mbps and very low delays between 25-40 ms.

Recent studies have investigated the use of wireless communications in V2G environments. The study in [81] details the communication requirements to gather data from various entities such as EVs and the grid and other grid resources as well as to communicate with EVs for control purposes. The technologies, protocols and block components needed for enabling IP communications in mobile V2G environments are discussed in [82]. A smart charging system which acquires EV data and transmits control instructions to the charging station via GPRS and ZigBee is proposed in [83]. The study in [76] presents two IEEE 802.11p-based quality of service schemes that enable the interaction between EVs and the grid for coordinated EV charging. The study in [84] modeled the average delay time for a group of charging EVs based on Markov chain representation for the wireless IEEE 802.11 MAC protocol, which considers the impact of a lossy wireless link between EVs and the access point. The study in [85] proposed an EV charging management scheme utilizing vehicular communication between EVs and access points based on IEEE 1609 WAVE and IEC 61850 standards. A software-defined networking-based control scheme for vehicular communication networks is developed in [86]. An EV charging scheduling scheme which considers the impact of data communication unavailability on the charging station scheduling performance is developed in [87]. A joint optimization model of energy cost and radio usage for discharging EVs in V2G communication networks is proposed in [88].

4.2. Data Analytics

EVs will be an integral part of the modern era of low latent wireless communications that promises to provide low-latency and ultra-reliable transmissions [89]. 5G network aims to support the deployment of vehicles to everything (V2X) technologies, carter to explosive ever-growing data traffic and enable users to indulge in gigabit speed immersive services capable of extremely low response time, regardless of geographical and time dependent factors. V2X technology will facilitate autonomous energy trading, where EVs in parking lots can autonomously charge and discharge their batteries, while self-driving EVs can be routed to appropriate charging stations to participate in EVaaS activities. EVaaS requires much shorter network response time and big data analytics to enable rapid reactions and intelligence across the network. There is no doubt that large amounts of data will be generated by sensors, smart meters, cameras, maps, on-board electronic control unit and battery management system of EVs, databases and more.

EV data which can be used to monitor, analyse and make decisions relating to charging/discharging, energy trading and range estimation mostly come from the on-board electronic control units and battery management system. EV data can be categorized as into three types, namely standard, historical and real-time data. Standard data include technical specifications from manufacturer and the usual driving time to destination according to Google Map. Historical data include battery management system logs showing start and end times of journeys, as well as SOC information like connect and disconnect times of charges and discharges. Real-time data include SOC of EV battery, GPS location of EV and data closely related to emergency issues, such as unplanned road closures and real-time traffic/weather condition. Internet of things (IoT) enables the recording and transmitting of detailed EV data in on-board computers or cloud computing infrastructure. In the context of the smart grid, IoT is built by integrating internet-connectivity into all grid subsystems, connecting them in intelligent networks, and utilizing data analytics to extract meaningful and actionable insights from them [90]. Cloud computing provides the virtual infrastructure for data collection, analysis and visualization in the current architecture of IoT.

During mobility, autonomous EVs can generate data up to thousands of gigabytes, where the volume of data is dependent on the variety of sensors and cameras used for autonomy. Data generation is not expected to be enormous during EVaaS, but the various sensors collecting data from grid, EVs, smart meters, charging stations and drivers will need solutions from the big data domain. Effective integration of data from different sources is possibly an enormous task; however, with the right tools and solutions from the big data domain, valuable insights can be drawn [91]. Prioritizing the intercepted information is essential and means of prioritization should be investigated, as decision-makers can only digest a certain amount of information and draw insights based on it. Furthermore, the processing of EV data by the aggregator make EVs vulnerable to security and privacy concerns, which are yet to be addressed in the domain of big data analytics for EVs.

5. Charging Strategies

Large-scale deployment of EVs will result in higher demands on distribution systems, which were not originally designed to withstand a high level of EV penetration [92]. With the expected rise in penetration levels, future EV charging scenarios could be accompanied by numerous challenges. EV charging profile has an effect on the distribution system. The increasing number of charging EVs adds extra load on distribution systems, which can drastically impact electricity grid stability. These impacts include power quality issues, phase imbalance, transformer degradation and failure, higher system losses and increased operational cost [93]. We review different charging strategies and their impact on distribution systems. This review classifies the EV charging strategies into uncoordinated and coordinated strategies.

5.1. Uncoordinated Charging

Uncoordinated charging describes a scenario where the EV batteries either start charging immediately EVs are plugged into a charge point or after a user-adjustable fixed delay, and continues charging until the batteries are completely charged or unplugged. In uncoordinated charging, EV charging is presumably at Level 1 with no coordinative control action. Thus, its impact on distribution systems is primarily driven by the stochastic behaviour of the EV user [94]. Load at peak hours tend to increase with uncoordinated charging operations. An increase in peak load can cause severe network stress and overloads in the local distribution grid. Random uncoordinated charging may lead to increased power losses, overloads in transformer and cables, poor voltage profiles, degraded power quality and an overall reduction in the reliability and economy of the distribution grid [95].

An analysis into the impacts of random uncoordinated EV charging on the performance of distribution transformers was carried out in [96]. Results revealed that even under low EV penetrations, transformer load surging and voltage deviations were significant. Load growth on transformers for low penetration level of 17% to 31% showed a 37% to 74% increase in transformer load current. In [97], a test model using household load profiles for Belgium reports voltage deviations close to 10% during evening peak for a penetration level of 30%. A typical UK distribution system is studied in [98] to determine the impact of uncontrolled domestic charging on the distribution system. Results show up to 17.9% increase in daily peak demand at 10% penetration rate of EVs, while the peak load would increase by 35.8% at 20% EV penetration. In [92], the impact of EV penetration on existing electricity distribution infrastructure was analysed using data for the Netherlands. Results show that at 30% EV penetration, uncoordinated charging would increase national peak load and household peak load by 7% and 54%, respectively, which may exceed the capacity of the distribution system. The utility operator will have to increase peak generation if the load exceeds peak capacity. The cost of additional generation capacity during peak period is then passed on to EV owners. In [99], uncontrolled charging was shown to cause a 22% increase in the monthly energy bill, even at just 10% EV penetration.

Some energy suppliers in the UK offer EV tariffs to help reduce peak demand, redirecting it to off-peak times [100]. The two-rate tariff, which offers cheaper rates during off-peak times (overnight), is designed to encourage EV owners to charge when the energy demand is low, and generation is mostly base load. The study in [98] showed that overnight charging increases off-peak energy consumption but it had no impact on the daily peak load. In [92], off-peak charging at 30% penetration rate of EVs was reported to cause a 20% higher, more stable base load and no additional peak load on the national grid. Thus, with the introduction of off-peak charging, additional generation capacity would not be required for low EV penetrations.

5.2. Coordinated Charging

Coordinated charging is being investigated as an alternative and possible solution to random uncoordinated charging and its associated problems, respectively. EV charging is most likely at Levels 2 and 3 in coordinated charging [19]. By utilizing the control and bidirectional communications infrastructure of smart grids, smart coordinated charging and discharging of EVs can reduce transformer load surges, line currents, voltage deviations and daily energy costs [95,97,101]. It can also provide efficient energy usage [98] and flatten the voltage profile of a distribution node [102]. Incremental distribution network investment and energy losses costs can be avoided with the implementation of smart charging strategies. Results in [103] showed the possibility of avoiding up to 60%-70% of the required incremental investment with smart charging. The results of the study in [104] reveal that coordinated charging of EVs minimizes system losses and improves voltage regulation in the distribution grid.

Smart charging and discharging where EVs charge their batteries from RESs and discharge them during peak demand is reported to offer the best possible utilization of RESs for cost and emission reductions in the smart grid [105–107]. It can improve operational performance in stand-alone operation mode and increase the quantity of RESs installed in islanded microgrids [101]. A control strategy was implemented in [108] to coordinate the charging and discharging of EVs to support a grid with high penetration of wind energy. The obtained results showed that the total power imbalance in the system was significantly suppressed. In [109], coordinated EV charging and discharging was implemented on an Australian distribution grid with solar power generation. The proposed control method was able to cope with solar power uncertainty and efficient in improving grid performance, reducing energy cost and mitigating grid imbalance.

Coordinated charging can be categorized into two types, namely centralized and decentralized approaches. In centralized approaches, EV charging is directly controlled by a centralized unit (microgrid control centre or aggregator). Centralized approaches offer full support for ancillary services. However, only a limited number of charging EVs can be accommodated. Another drawback of this approach is that it involves higher order complexity. In decentralized approaches, the power of decision-making with regards to EV charging is distributed among individual EVs. The charging behaviour of EVs can be directly influenced by a price signal. Decentralized approaches offer greater scalability and lesser computational complexity. Considering EVs only have to exchange limited information with the aggregator, their privacy is preserved [110]. A drawback in this approach is the need for EVs to collect and store the trip history [111]. Compared with centralized approaches, the decentralized approaches are more scalable, flexible, and enables EV owners to partake in the decision-making process of EV charging.

6. Energy Trading and Market Design

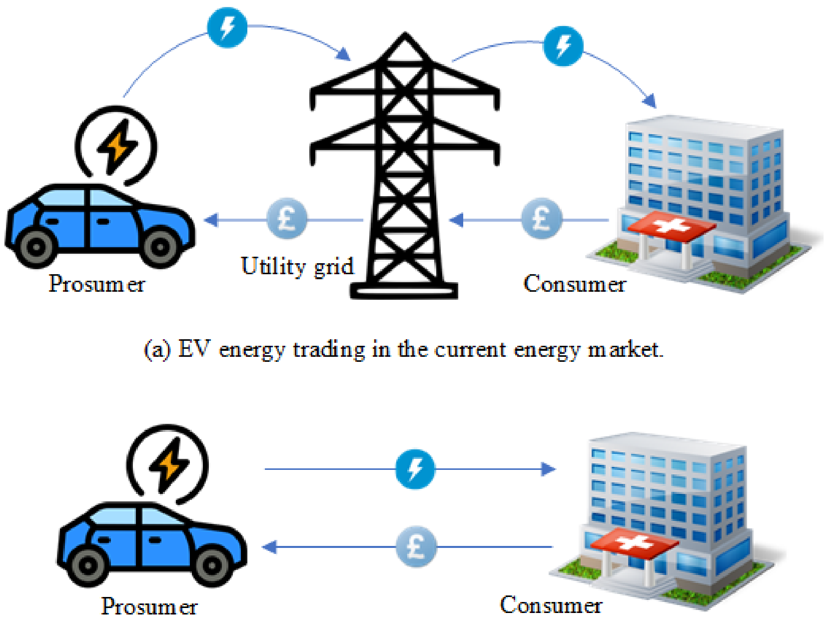
Advances in V2G promises unprecedented improvements in operational efficiency. This unlocks the possibility of prosumer and consumer participation in energy trading. Consumers equipped with rooftop solar power system can emerge as EV-prosumers and self-supply during peak period or power outages using V2H integration [112]. This can lead to reduced household energy costs, maximum utilization of solar power generation and minimum dependency of domestic loads on the grid. In an EVaaS energy trading scenario, a grid manager (aggregator) has a demand target and manages individual or aggregated EVs to fulfill the demand. Energy trading can be categorized according to the market design. We review two types of energy trading in V2G environments: traditional bilateral energy trading used in conventional energy industry and futuristic energy trading with increased distributed influence, based on blockchain technology.

6.1. Traditional Energy Trading

Traditional energy industry has operated on a centralized energy trading model for decades. In centralized approaches, one user or a centralized controller dictates to a group of users, while acting collectively as one entity. The central controller, acting as an energy broker, is assumed to know all the information about trading entities and tries to match demand and supply. The appropriate framework to employ in a centralized market would be single objective optimization models such as swarm, stochastic or convex optimization, or social welfare maximization [113]. Decentralized energy markets enables scalability and competitiveness amongst self-interested EVs compared to their centralized counterparts. Thus, it is important to investigate distributed economic approaches which incentivizes energy trading between EVs and the grid [114].

Auction is a promising market mechanism used to sell (forward auction) or buy (reverse auction) energy in smart grids, with the aggregator acting as auctioneer. In a scenario where energy trade is incentivized, buyers pay a discount in forward auction while sellers receive a premium in reverse auction as compared to the clearing price. The amount of energy to be traded and the final price to be paid is the outcome of the auction. Based on the final payment, there are different auctions schemes, namely first price auction, second price auction and uniform price auction [115]. Utility-maximizing bidders could misrepresent their valuations (individually or collusively) by not bidding truthfully, which could harm the fairness and efficiency of the trade. Vickrey-Clarke-Groves (VCG) auction is effective in ensuring the properties of truthfulness [116–118]. An auction scheme that enables EVs and batteries in swap stations to trade energy is proposed in [119]. A double auction-based approach for enabling EVs to trade their excess energy to the grid is studied in [120]. Double auction mechanism has also been studied in [121,122] for energy trading in a two-layer V2G architecture, made up of grid-aggregator and aggregator-EV layers. In [123], a group-selling strategy for V2G demand response management is implemented through a two-layer reverse auction.

Game-theoretic approach is another promising solution which has been used in numerous applications to study the interactions among self-interested and independent agents. A game is made up of three essential elements: a set of players, a set of actions (strategies) and a set of payoffs (utility functions). The payoff obtained by the players is the value of the game. One major strategy for game theory is the Nash equilibrium, where no player has any incentive by unilaterally deviating from its strategy. Based on players coordinating or competing with themselves, games can be categorized into two types, namely cooperative games and noncooperative games. Noncooperative games are appropriate in distributed energy trading scenarios between competitive trading entities. While cooperative games are ideal in scenarios where trading entities cooperate with the aid of communication networks, in other to optimize the efficiency or social welfare of the collaborators. In [124], an analytical framework that captures the interactions between a smart grid and EV groups is modelled using a noncooperative Stackelberg game. The interactions and energy trading decisions of geographically distributed storage units, such as EVs, is studied in [125] using a noncooperative game. An incentive-based V2V game theoretic approach that captures the coordination strategies of EVs and battery swapping station aggregators is modelled in [126]. In order to incentivize EV participation, each battery swapping station aggregator implements a noncooperative game among the EVs in its range through a smart pricing scheme. Collaborative and non-collaborative approaches which considers energy trading and residential load scheduling with EVs is proposed in [127]. The collaborative approach is based on social welfare maximization, while the non-collaborative approach utilizes a noncooperative game. Besides auction and game theory, incentive-based approaches such as pricing, bargain and contract theories, which are able to study the interaction between self-interested participants and improve the efficiency of energy trade, have been widely deployed [114].



(a) EV energy trading in the current energy market.

(b) EV energy trading in a peer-to-peer (P2P) manner.

Figure 2. Types of energy trading in V2G environments.

6.2. Blockchain-Based Energy Trading

With the rising penetration of EVs, satisfying the ever-increasing energy demand of V2G applications remains a challenge for the distribution system. To address this challenge, recent studies have exploited blockchain technology for energy trading in V2G environments. Blockchain technology enables increased distributed influence in the distribution system, while preserving privacy and maintaining transparency and system security [128]. This will improve the flexibility of the conventional energy market, enable a consumer-centric energy market and support prosumer participation. EVs, acting as prosumers or consumers, will be able to trade energy in a peer-to-peer (P2P) manner without third-party intervention as shown in Fig. 2.

The application of blockchain technology for EV-enabled energy trading in smart grids is briefly discussed in [129]. A decentralized security model based on the lightning network and smart contracts is proposed in [130] to protect energy trading transactions between EVs and charging stations. A localized P2P energy trading model based on consortium blockchain is proposed in [131]. The model uses iterative double auction mechanism to maximize social welfare of charging and discharging EVs. Consortium blockchain has also been exploited in [132] to propose an energy trading model applicable in general scenarios of P2P energy trading. The model uses Stackelberg game to maximize economic benefits. Blockchain technology was applied in [133] to establish a trusted environment for energy trading between EVs and critical loads and a prototype was developed for remotely monitoring of energy trading activities.

While P2P energy trading is promising, one of its major impediments is regulation. Currently, decentralized energy trading is prohibited by regulation in the UK and some other EU countries, however this could change in the future. Business owners or individuals who generate electricity are limited to use it on site or sell directly to the utility grid for a nominal price. This poses a major barrier to P2P energy trading which enables direct trade between prosumers and consumers, instead of selling to and buying from the utility grid, respectively. Ideally, the authorization of P2P energy trading will create a competitive energy market, allow prosumers generate revenue on their excess energy and consumers obtain cost effective energy. It is expected that energy prices will drop as a result of eliminating the middle man and more individuals incentivized to partake in microgeneration.

7. Benefits of V2G

7.1. Ancillary Services

V2G systems facilitates and encourages EVs participation in V2G, where EVs offer various ancillary services to the electric power grid. Ancillary services are essential for balancing demand and supply, maintaining grid reliability and supporting power transmission.

7.1.1. Reserve Power Supply

V2G systems can maintain the balance between demand and supply in electricity grids by injecting power. While the supply capacity for individual EV is small, an aggregated capacity can be significant to provide value to the grid. Aggregators are expected to collect EVs into a group to create a more desirable, larger electricity generation capacity for the utility. For example, by simultaneously discharging their batteries, aggregated EVs will be able to provide additional power required by commercial building during peak demand, acting like a spinning reserve power generation source in the existing distribution system.

7.1.2. Voltage and Frequency Regulation

V2G systems are capable of regulating voltage and frequency in electricity grids. Frequency regulation provides active power support in the electricity grid. The exact amount of electricity being used needs to be matched by generation, if there is an imbalance it can affect the frequency of the electricity grid. For example, if electricity demand is more than supply, frequency will fall. If there is too much power being generated in relation to demand, frequency will rise. The frequency will not stabilize until the system in balanced. In the UK, anything just 1% above or below the nominal frequency of 50Hz risks damaging electrical equipment and infrastructure, including appliances of end users. Currently, frequency regulation is achieved mainly by turning on fast-responding generators to increase power generation, which is costly. Alternatively, fast charging and discharging rates of EV batteries can help to increase the load demand and generation, respectively. This makes V2G a promising alternative for frequency regulation [134,135]. Voltage regulation provides reactive power support in the electricity grid. Reactive power can be controlled by selecting the current phase angle to provide inductive or capacitive action. The consumption of reactive power is mostly through inductive load, which requires the addition of capacitive reactive power to balance the demand. Traditionally, reactive power support is injected at the transmission or distribution grid stage, with no involvements from the end-users. However, with increased EV penetration, V2G can provide the necessary reactive power support to the grid.

7.1.3. Peak Shaving and Load Levelling

V2G systems are capable of levelling peak loads in electricity grids. Peak load shaving is achieved through a control strategy that manages EV charging and discharging. In this technique, controllable and aggregated EVs can charge when demand is low (off-peak hours or overnight) and discharge during high demand (peak hours). In scenarios where the generation capacity does not match the peak demand, several problems such as voltage fluctuation, instability and total blackout could possibly occur. Therefore, by shaving peak load, the reliability and stability of the grid is maintained and supply shortage is mitigated. Previous studies had proposed different peak shaving and valley filling techniques through V2G to alleviate the generation-demand imbalance [104,136,137]. This function of V2G can provide economic benefits as it limits the need to use high-priced peak generators.

7.2. Mobile Backup Power Supply

V2G systems are capable of restoring supply during prolonged grid outages and can improve the grid capabilities to withstand unexpected contingencies. Power systems must not only operate reliably in response to foreseeable contingencies, but also resilient to high-impact low-probability events [138]. Keeping critical loads operating during prolonged grid outages is a key resilience feature for mitigating its consequences [139]. Thus, following an unexpected system failure, fast recovery is very essential to enhance grid resilience. EVs, as mobile power generation and storage resources, can distribute the existing energy produced or stored in the local region. Aggregated EVs will be able to provide backup power required by critical loads during a blackout. In a scenario where the distribution network is partly damaged during an extreme event and regular supply cannot reach critical loads, EVs can be deployed to individual locations of the critical load to restore supply [133].

7.3. Renewable Energy Supporting and Balancing

V2G systems can support intermittent renewable energy in electricity grids. Due to the intermittent nature of wind and solar plants, their large-scale integration into the current electricity grid would require a large-capacity scale storage system [140–142]. For instance, peak solar radiation precedes peak demand by a few hours – solar peak power is at noon, peak demand is typically between mid-afternoons to late afternoons. On the other hand, the stochastic nature of wind power is due to unpredictable variations in wind speed. Wind generation fluctuates and cannot be turned up when energy demand increases, leading to imbalances. At low scale penetration, existing mechanisms for managing supply and demand fluctuations can handle the intermittency of renewable energy. However, at high levels of penetration, additional resources are needed to match the fluctuating supply to the already fluctuating demand. If there is too much energy being generated from renewable sources, generation from conventional power plants must be curtailed to restore balance. EVs can help match generation and consumption by charging and discharging so the utility does not consider decreasing the power output. Thus, V2G increases the flexibility of the grid to support intermittent renewables.

7.4. Environmental Benefits

V2G systems can offer societal benefits regarding climate change, GHG emissions and air pollution. Climate change benefits come about via controlled charging (or peak shaving) to limit usage of high carbon energy sources, decarbonisation of the ancillary service market and electrification of the transport sector. The carbon benefits of V2G are mostly dependent on the electricity generation mix of the grid. In electricity grids with high polluting sources, V2G providing ancillary services has potentials to increase total carbon emissions [143]. EVs cannot guarantee decarbonisation since they are not generation. If EVs charge their batteries from a grid with high penetration of coal in its generation mix, their environmental advantages are more limited. However, if EVs are powered by cleaner energy sources, they can help reduces GHG emissions [144,145]. From a transportation perspective, EV penetration possess potentials to reduce air pollution compared to ICE vehicles [146]. Direct emissions from ICE vehicle activity has an effect on public health, agriculture and natural environment. Thus, high penetration of EVs diminishes health and environmental costs.

8. Challenges to V2G

8.1. Battery Degradation

Despite the many benefits V2G offers, a major concern has been its impact of on the degradation of EV batteries. V2G operation imposes more use (and stress) on EV batteries compared to daily driving, which likely accelerates the aging of EV batteries [147]. This can be associated with the increase in charge cycle, where a charge cycle is a complete charge and discharge process on the battery. EV battery usage is limited to a fixed number of cycles, over time the capacity (amount of energy that can be stored or extracted from the battery) degenerates significantly. Recent studies have found that degradation costs are a substantial barrier to the grid, while others found degradation to be minimal. Determination of V2G impact on EV battery degradation is still at the research stage with recent studies arriving at contradictory conclusions. While some studies found degradation costs to be a substantial barrier to V2G [148,149], others found degradation to be minimal [150,151]. Nevertheless, even in the best-case scenario, participation in V2G operation accelerates battery capacity degradation beyond what is required to satisfy the driving demands [152]. Consequently, EVs may be expected to undergo battery replacement multiple times over their service life. Thus, V2G influences the frequency of battery replacement and associated costs.

8.2. Energy Conversion Losses

In V2G systems, energy losses occur between the grid connection point and the EV battery. Each time EVs are charged or discharged, energy losses occur in the EV and its supporting electrical infrastructure such as charging station, breakers and transformer. Each stage of storage, conversion and transmission contribute to the losses. This is considering the efficiencies of system components such as EV battery, power electronic unit, charging station, breaker panel and transformer. The impact of different levels of EV penetration on the distribution network was studied in [103]. Under studied conditions, obtained results showed that energy losses could increase up to 40% with the respect to the level of EV penetration. In [153], energy losses from electricity grid to EV battery and back to the grid were measured experimentally. The measured total one-way losses were up to 36%, under studied conditions. Although studies have reported round-trip losses for EVs and related V2G infrastructure, efficiency values are case dependent and will differ among EVs and electrical circuits. Nevertheless, they can serve as a reference point for future studies on economic analysis of V2G.

8.3. Effects on Distribution System

The increasing penetration of EVs is likely to have considerable impact on the distribution system. Since the distribution grid is still focused on conventional design and operational rules, service capabilities of V2G devices tend to be limited. The charging and discharging of EVs introduces a change in the overall load profile of the distribution system. Uncontrolled EV charging adds to the pre-existing peak load, especially during fast charging. The load demand is centralized at the fast charging station and fast charging mainly occurs during the daytime, allowing EVs draw high power larger than a regular household load [154]. The interconnection of fast charging stations with the grid might create negative impacts on the distribution system [155]. Fast charging of EVs could result in detrimental effects on distribution transformers, lower operational efficiency of the distribution network equipment and rise in energy losses. Fast charging also has adverse effects on the voltage profile and power quality of the network. Additional EV load increases transformer temperatures, which contributes to insulation breakdown and may decrease the life expectancy of the transformer [156]. The impact of different penetrations of EVs on a residential distribution transformer was studied in [157]. This revealed that high penetration of EVs can have significant impact on the electricity grid, particularly in scenarios with uncoordinated charging. In [158], an investigation was carried out to evaluate some of the effects of EV deployment on existing distribution network. This revealed that high deployment of EVs could result in supply and demand matching and statutory voltage limits violations, as well as voltage imbalance and power quality problems. In order to help the distribution circuit to accommodate EV penetration, a demand response strategy is proposed in the context of a smart distribution network in [159]. Thus, the effect of V2G on the distribution network is greatly influenced by the charging strategies and vehicle aggregation [160].

9. Conclusion

V2G technology enables EVs deployment as loads to absorb excess production or as generators to feed-back surplus energy to the distribution grid during peak demand or system failure. This paper has presented an EVaaS system where EVs, individually or as part of an aggregation, can provide service to the grid, individual customers, or both. The EVaaS system architecture and interactions among EVaaS subsystems such as EV battery, charging station, load and advance metering infrastructure has been discussed. The infrastructure and processing facilities for bidirectional communications in V2G environments has been explained. Several potential battery technologies that might be able to match the widely accepted Li-ion batteries were highlighted. Methodology to enhance grid resilience through building load categorization was introduced. The impact of coordinated and uncoordinated and fast charging on the distribution grid was discussed. The challenges associated with timely utilization of solar-powered EV charging stations was examined. The centralized structure of conventional energy markets does not allow the full potential of V2G to be realized. The current energy market is not consumer-centric and does not support prosumer participation. Policy change, supporting infrastructure and incentives would play a huge role in maximizing the market opportunities presented by V2G.

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