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Bidirectional Charging Hubs in the Electric Vehicle Retail Landscape: Opportunities and Challenges for the U.K. Case

I. SAFAK BAYRAM (Senior Member, IEEE) AND XIANG SHI (Student Member, IEEE)

Department of Electronic and Electrical Engineering, University of Strathclyde, G1 1XQ Glasgow, U.K.

CORRESPONDING AUTHOR: I. SAFAK BAYRAM (e-mail: safak.bayram@strath.ac.uk).

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ABSTRACT In light of governmental policies phasing out petrol/diesel car sales, the vehicle retail sector is transforming to focus solely on electric vehicles (EVs). Given their available physical space and access to a high volume of EVs, future vehicle retailers are ideally positioned to operate as bidirectional charging hubs. This paper explores the challenges and opportunities this presents for EV retailers. Current EV battery technology is examined, including degradation mechanisms associated with grid-to-vehicle and vehicle-to-everything applications. Next, bidirectional chargers and relevant industry protocols are analyzed in detail. The U.K. energy market's ancillary services are also investigated, with a focus on the specific performance requirements of different market types. Leveraging publicly available datasets from six mainstream EV models, the suitability of various EV fleets for each market is assessed. Finally, recent V2G projects are analyzed, and the broader societal implications of bidirectional charging hubs are discussed.

INDEX TERMS Ancillary services, Bidirectional charging, electric vehicles, EV retailers, lithium-ion battery, V2X.

I. INTRODUCTION

A. MOTIVATION

There is a global motivation to reach net-zero to mitigate the disruptive impacts of climate change. One of the most challenging transitions is taking place in the transportation sector, the largest emitter of greenhouse gas emissions [1]. With the increasing number of electric vehicles (EVs) (by the end of June 2024, over 1.14 million battery EVs were registered in the U.K. [2]) and the surge in renewable energy generation (in the first quarter of 2024, 50.9% of the U.K.'s electricity generation came from renewable sources [3]), there is a pressing need to enhance the flexibility of power systems to buffer fluctuations in generation.

Vehicle-to-Grid (V2G), a concept that emerged at the end of the 20th century, has been extensively explored as EVs have become more prevalent. By enabling bidirectional power flow, V2G allows idle EVs to support the grid through charging (power import) or discharging (power export). Bidirectional charging hubs are public charging stations equipped with a variety of chargers that facilitate this two-way power flow, offering EV owners additional financial incentives [4].

While residential V2G charging has been widely explored [5], [6], existing demonstration projects faces challenges related to scalability, plug availability of EVs, and the high cost of metering equipment. Vehicle retailers, with their extensive networks and large fleets of vehicles, are well-positioned to overcome these limitations. These businesses collectively manage hundreds to thousands of vehicles, making them readily available for V2G participation throughout the day. Furthermore, a single measurement point per V2G hub could suffice, reducing the need for costly high-accuracy meters for certain energy market events.

In addition, car dealerships could strategically relocate inventory within their networks to support specific areas of the power grid as needed. Leveraging their widespread reach, retailers can also incentivize customers to engage in V2G sessions during critical grid events (e.g., peak hours), promoting both social responsibility and responsible charging practices.

TABLE 1. Comparison of Conventional Charging Hubs and Vehicle Retailers as Charging Hub

	New Hub Construction			Charging Service		V2G Participation	
	Location	**Physical Space**	**Network Connection**	**Customer Acceptance**	**EV Availability**	**Coordination**	**Inventory Movement**
Conventional Charging Hub	Lease/Purchase	Limited & expensive	New Connections	Open competition against other charging businesses	Depends on EV arrival/departures	Extensive coordination required with all customers	N/A
Vehicle Retailer as Charging Hub	Existing (100s) of locations	Existing company assets	Reinforcements	Serve existing customer database and general public	On-site large stationary fleet	Single coordination with Retailer Business Owner	Could be moved with 24h of notice

A prime example is Arnold Clark, the largest vehicle retailer in the U.K., with an extensive network of company-owned retailers, service centers, and other operational facilities. As of July 2024, within a 10-mile radius of its headquarters in Hillington, Glasgow, the company has 529 EVs and 5,446 vehicles of all types [7]. The proportion of EVs in this fleet is expected to rise significantly in line with EV sales trends. Notably, Arnold Clark has recently introduced private ultra-fast charging hubs at its branches across the U.K. [8]. The size and ownership structure of such an EV fleet present a unique opportunity to provide ancillary services to the grid, while the vast real estate network could serve as an ideal platform for delivering convenient charging services, thus enhancing the EV ownership experience.

B. RESEARCH GAPS AND CONTRIBUTIONS

The design and operation of electric vehicle (EV) charging hubs have recently emerged as a critical area of research [9]. Existing studies predominantly focus on public charging hubs serving the general public, with their capacity and ability to participate in energy markets contingent on vehicle utilization, types, and driver incentives. However, EV retailers offer distinct advantages over public charging hubs due to their existing land ownership and vehicle fleets, which significantly reduce uncertainty related to EV occupancy. Table 1 provides a comparative analysis of conventional and vehicle retailer charging hubs, underscoring the advantages of the latter in construction, charging services, and V2G potential.

Despite their potential significance, the role of EV retailers remains largely unexplored in the literature. Early research in the 2010s focused on bidirectional power flow and theoretical V2G applications. The introduction of the V2G-capable Nissan Leaf in 2014 marked a turning point, followed by a period of literature surveys addressing general V2G opportunities and challenges [5], [10], [11]. From 2019 to 2024, field trials and demonstration projects proliferated globally, with the U.K. emerging as a major investor. Simultaneously, a growing body of research has investigated EV batteries and ageing profiles, essential for V2X system understanding.

However, a comprehensive review encompassing recent advances in EV batteries, degradation mechanisms, cutting-edge chargers and standards, updated U.K. ancillary service requirements, and the social impact of EV retailer charging hubs is currently absent. This review paper seeks to address this gap by analyzing relevant publications from the past decade. Moreover, it offers unique contributions, including:

- An updated inventory of V2X-capable EVs, comprehensive vehicle and battery statistics, and a comparative analysis of competing battery technologies and their associated ageing models.
- A detailed examination of current external and onboard EV chargers, their applications in bidirectional charging, and real-world data collected from six mainstream EV models.
- A comprehensive overview of recently updated ancillary services suitable for V2G applications, encompassing technical specifications and a methodology to assess the suitability of existing EV fleets for specific market types.
- An analysis of current ancillary service market data published by the national service operator, an overview of recently completed V2G demonstration projects, and a detailed examination of the opportunities and challenges confronting EV retailers as potential charging hub operators.

C. PAPER OUTLINE

This section outlines the key components of a bidirectional charging hub and details the structure of this paper. Section II delves into EV battery technology, encompassing the distribution of battery capacities across EV models, key terminology, and a comparative analysis of various battery chemistries. In the context of conventional EV charging, hub utilization is influenced by factors such as battery size, charging rate, parking duration, and customer demand (in kWh). When these facilities enable V2G services, additional factors come into play, including battery degradation from discharging, total available power, and energy capacity. Section III provides a comprehensive analysis of degradation mechanisms, types, and existing research findings in this area.

Section IV focuses on charging standards, cables, and sockets, emphasizing the importance of these components in light of regional and vehicle-specific variations that can impose constraints on EV charging/discharging. For EVs, communication delays associated with initiating charging sessions and adjusting charging/discharging rates are critical vehicle-specific parameters, particularly in ancillary services markets with stringent response time requirements (often less than a second). A detailed analysis of these communication delays and their implications for energy markets are discussed in

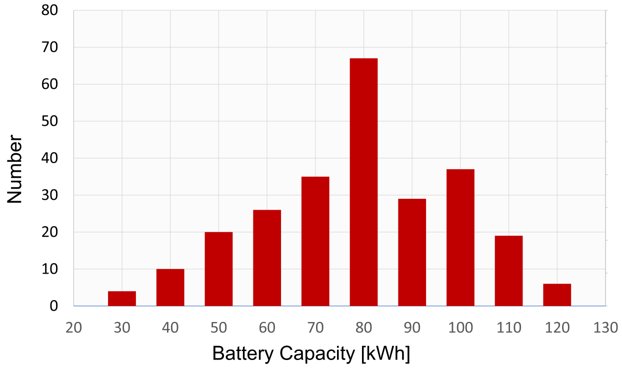

FIGURE 1. **Histogram of EV battery capacity (kWh) and its empirical distribution (vehicle data collected in 2024 from [12]. (Mean: 74.53 kWh Standard deviation: 20.22 kWh.)**

Section VI a long with ancillary services markets in the U.K. Building on the analysis from earlier sections, it examines the suitability of different EV models for various applications, assessing their ability to meet minimum requirements (e.g., response time, capacity) set by the National Grid for different energy markets (e.g., frequency regulation, reserve).

The social impact of EV charging hubs, particularly how their location can influence EV adoption rates in neighboring communities, is explored in Section VIII. Finally, Section IX provides a general discussion, outlines open research questions, and presents concluding remarks.

II. EV BATTERY TECHNOLOGY

A. OVERVIEW

Batteries are electrochemical energy storage devices that provide the necessary power to propel EVs. As the transition to EVs intensifies, there is a growing reliance on batteries, with better and more affordable options at the forefront of the manufacturing market [13]. In 2023, the demand for EV batteries surpassed 750 GWh, marking a 40% increase from 2022. Electric cars accounted for 95% of this surge. Globally, the rise in EV battery demand was primarily driven by higher sales of electric vehicles (95%), with the remaining 5% attributable to larger average battery sizes, particularly from the growing SUV segment within electric car sales. Among major EV markets, the United States and Europe saw the fastest growth, each exceeding 40% year-on-year, while China followed closely at approximately 35%. Despite this growth, the United States still had the smallest market, with around 100 GWh in 2023, compared to 185 GWh in Europe and 415 GWh in China [13].

In line with the growing demand for EVs, energy storage technology has improved significantly, and the size of EV batteries has more than doubled over the last decade. In 2014, the average pure EV battery pack was less than 30 kWh, with a few Tesla models exceeding 50 kWh [14]. Fig. 1 presents a histogram of the battery sizes of current EV models. The distribution of battery pack sizes varies between 20 and 120 kWh, with a mean of 80 kWh. Considering that the average daily driving range is less than 20 miles in the U.K. [15] and in most European countries [16], the current size of battery packs presents an opportunity for EV drivers to exploit added value through vehicle-to-everything (V2X) applications, which are discussed next.

B. VEHICLE-TO-X

Vehicle-to-everything (V2X) refers to the ability of EVs to interact with various systems, including the grid (vehicle-to-grid or V2G), homes (vehicle-to-home or V2H), loads (vehicle-to-load or V2L), buildings (vehicle-to-building or V2B), and other vehicles (vehicle-to-vehicle or V2V). Typical V2L applications include powering appliances that require less than 2–3 kW of power, such as camping equipment, e-bikes, and even cooking appliances during blackouts following disasters [17]. V2L technology incorporates an onboard converter within the vehicle to transform Direct Current (DC) from the battery into Alternating Current (AC) for V2L use. This technology is integrated within the vehicle itself, not in the adaptor. The adaptor manages the load and facilitates power transfer to the cable, while the vehicle internally handles the conversion from DC to AC and power management. A detailed list of EVs that can provide V2L is given in Table 2.

V2H operates similarly to V2L, but instead of feeding energy back to a specific load, the EV battery powers an entire home. This allows the EV to act as a household battery system, providing backup power during a blackout. To enable V2H, a compatible bidirectional charger and additional equipment, such as an energy meter (CT meter), are required. The CT meter monitors the energy flow to and from the grid. When it detects energy consumption by the home from the grid, it signals the bidirectional EV charger to discharge an equal amount of energy, offsetting the power drawn from the grid. On the other hand, V2V and V2B applications have received limited attention and their applications are still in the development/demonstration phase [18].

V2G involves utilizing the energy and power capabilities of EVs to offer services to grid management entities, also known as Ancillary Services. The scope of services for V2G is broader than that of V2H and V2B. Due to their scale, charging hubs are ideal locations for providing V2G services. Given the variety of markets, services, and specific tasks encompassed by V2G, Section VI offers a detailed overview and categorizes these markets into sub-categories within the V2G framework.

Table 2 presents the publicly available electric vehicles with V2X capabilities. During the 2010s, V2G-capable vehicles were very limited, with the Nissan Leaf widely used in demonstration projects. However, as shown in Table 2, there has been an accelerated interest from manufacturers to introduce new V2X-capable vehicles since 2021. Notably, the VW ID4 was released in 2021, but its V2G capability was not enabled until 2023 [19]. Table 2 also presents the type of battery chemistry used in each vehicle. A detailed discussion on different battery chemistry types is presented in the next Section II-D.

A comparison of V2G applications in terms of controllability and interconnection is presented in Fig. 2. Uncontrolled

TABLE 2. **Bidirectional-Capable EVs [12], [21], [22]**

EV	Battery Useable Capacity	Battery Chemistry	Capability	Max Output Power
Audi Q4 e-tron (2021)	77 kWh	Li-ion (NMC) [23]	V2H V2G	Not Announced (DC)
BYD Atto 3/Seal/Dolphin (2023)	60.5-82.5 kWh	Li-ion (LFP)	V2L	3.3kW (AC)
BYD Atto 3/Seal/Dolphin (2023)	60.5-82.5 kWh	Li-ion (LFP)	V2L	3.3kW (AC)
Ford F-150 Lightning (2024)	98-131 kWh	Li-ion (NMC)	V2H V2G	2.4kW (V2L AC) 9.6kW (V2H AC)
Genesis GV60 (2022)	74 kWh	Li-ion (LFP)	V2L	3.6kW (AC)
Hyundai Kona (2023)	48-65 kWh	Li-ion (NMC622)	V2L	3.6kW (AC)
Hyundai Ioniq5 (2023)	80 kWh	Li-ion (NMC)	V2L	3.6kW (AC)
Kia EV6 (2021)	74 kWh	Li-ion (NMC) [24]	V2L	3.6kW (AC)
Kia EV9 (2021)	96 kWh	Li-ion (NMC)	V2L V2H V2G	3.6kW (V2L AC) 11kW (V2H,V2G AC)
Kia Niro (2021)	64.8 kWh	Li-ion (NMC) [25]	V2L	3.6kW (AC)
Mercedes-Benz EQS (2021)	108.4 kWh	Li-ion (NMC811)	V2L V2H V2G	Not available yet
MG ZS (2021)	49-68.3 kWh	Li-ion (LFP)	V2L	2.2kW (AC)
MG4 (2022)	50.8-61.7 kWh	Li-ion (NMC)	V2L	2.2kW (AC)
MG5 (2022)	57.4 kWh	Li-ion (NMC)	V2L	2.2kW (AC)
Mitsubishi Outlander	13.8 kWh	Li-ion (NMC)	V2H V2G	Not available yet
Nissan Leaf (2022)	39 kWh	Li-ion (NMC523)	V2L V2H	7.0kW (DC)
Peugeot e-3008/5008 (2024)	73-98 kWh	Li-ion (NMC)	V2L	3.6kW (AC)
Polestar 3 (2022)	107 kWh	Li-ion (NMC)	V2L V2H V2G	11kW (AC)
Polestar 4 (2023)	94 kWh	Li-ion (NMC811)	V2L	Not Announced
Renault 5 (2024)	40-52 kWh	Li-ion (NMC)	V2L V2H V2G	3.7kW (V2L AC) 11kW (V2H,V2G AC)
Skoda Enyaq 85 (2023)	77 kWh	Li-ion (NMC)	V2H V2G	Not Announced (DC)
Tesla Cybertruck	120 kWh	Li-ion (NMC811)	V2L V2H	9.6kW (V2L AC) 11.5kW (V2H AC)
Volkswagen ID4 (2021)	77 kWh	Li-ion (NMC)	V2H	10kW (DC)
Volvo EX90 (2022)	107 kWh	Li-ion (NMC)	V2L V2H V2G	11kW (AC)

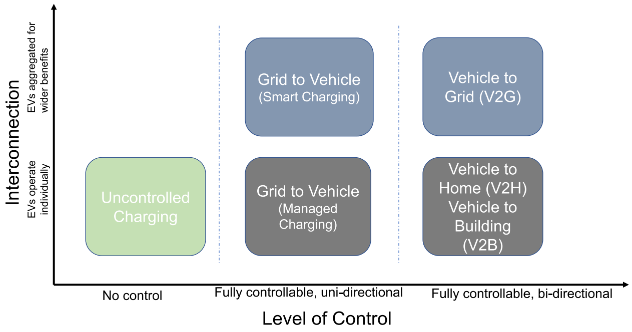

FIGURE 2. **Different levels of V2G applications (adopted from [20]).**

charging is the most basic EV charging method, where an EV starts charging at the rated power immediately after connecting to a charger. In this method, the charging current is constant, so there is no control over the demand. The terms "managed" and "smart charging" are used when the charging current of EV(s) is fully controllable to achieve a certain goal, such as minimizing peak power demand. Similar to smart charging, V2G applications have a very high level of control, as both charging and discharging currents are controlled. Therefore, the technical specifications of onboard chargers play a key role in V2G applications.

C. LITHIUM-ION BATTERY TECHNOLOGY

Lithium-ion (Li-ion) batteries are a critical enabling technology for EVs and dominate the EV market. A Li-ion battery consists of an anode, a cathode, an electrolyte, current collectors (positive and negative), and a separator [26]. The anodes, made of graphitic carbon, and the cathodes, made of lithium metal oxide, both store lithium. The electrolyte, composed of lithium salts dissolved in organic carbonate, acts as a medium for lithium-ion transport. Electrical current flows through the battery from an aluminum/copper collector across a device. Each current collector receives electrons from the external circuit, depending on whether the battery is charging or discharging. A porous polymer separator allows lithium ions to move freely between the anode and cathode while preventing electron flow within the battery. The cathode material is the key component of a lithium-ion battery, as it determines the key performance characteristics (e.g., capacity, energy density, etc.) of the storage unit. There are three main cathode types, which are detailed in the next section.

In the rest of the paper, key energy storage-related terms will often be used. Some of the key terms include State of Charge (SoC), Depth of Discharge (DoD), State of Health (SoH), and C-rate. SoC (in percentage) is the ratio of the current stored energy to the maximum usable battery capacity. DoD (in percentage) is the inverse of SoC and describes the amount of energy already used relative to the total battery capacity. SoH (in percentage) measures the extent of battery degradation due to age and usage, indicating its remaining capacity relative to its original capacity. Finally, C-rate is a unitless measure used to express the speed of charging or discharging a battery.

D. COMMON EV BATTERY CHEMISTRY TYPES

Lithium-ion (Li-ion) battery refers to a family of battery technologies that all store lithium but typically differ in

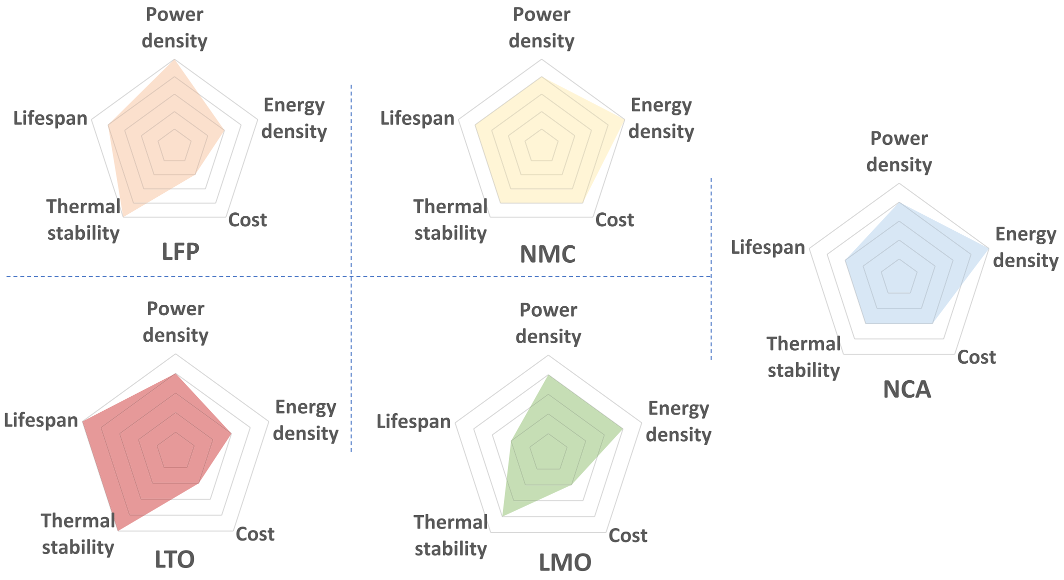

FIGURE 3. **Comparison of different lithium-ion batteries characteristics [28], [29], [30], [31], [32].**

their cathode material. Common Li-ion chemistries include Lithium Manganese Oxide (LMO), Lithium Titanate Oxide (LTO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Iron Phosphate (LFP) [27]. These different chemistries offer varying trade-offs in terms of energy density, power output, cycle life, safety, and cost.

In electric mobility applications, LCO was initially favored for its high energy density. However, safety and cost concerns have prompted the adoption of alternative Li-ion chemistries, such as LMO, LFP, and NMC. Notably, NMC has garnered significant attention due to its high energy density and is currently the preferred choice for major EV manufacturers seeking to maximize driving range. However, a trade-off between cost and driving range remains a challenge [33].

LFP batteries, despite a lower voltage levels, are valued for their environmental benefits, cost-effectiveness, and reliability in EVs. LTO and NCA are additional Li-ion battery types used in EVs. NCA batteries, renowned for their high energy density, are well-suited for applications prioritizing weight and space constraints. The inclusion of aluminum enhances stability, lifespan, and safety compared to other high-nickel-content Li-ion batteries.

While NCA batteries offer a higher energy density than NMC batteries, they may exhibit slightly lower stability and higher costs due to their elevated nickel and cobalt content. The choice of Li-ion battery type for a specific EV application hinges on factors such as energy density, cost, safety, and sustainability, as the technology continues to evolve rapidly.

An analysis of 50 EV models presented in [33] reveals that 76% EVs utilize NMC battery technology, followed by LFP (18%) and NCA (6%). Despite NMC's dominance in available models, sales of LFP-powered EVs have been notably higher, driven by robust sales from prominent brands like Tesla and BYD.

Fig. 3 compares five EV battery types based on thermal stability, lifespan (cycle life), power density, energy density, and cost. Key considerations when selecting an EV battery are the required power density and all-electric range, which dictate the battery pack design as the available space within the vehicle is also crucial. Thermal stability is paramount, as safety is non-negotiable in electric mobility. Overall, NMC demonstrates superior performance across most metrics, except for cost. Among all Li-ion types, NMC, LFP, and LTO exhibit relatively longer lifecycles. LFP and LMO batteries share similar characteristics, offering medium energy density, affordability, and safety.

III. EV BATTERY DEGRADATION

A. BATTERY AGEING MECHANISMS

Battery degradation, an inevitable consequence of electrochemical processes within a battery, is a pivotal concern in the electrification of transportation. The intricate mechanisms driving this degradation encompass both capacity fade and associated costs, significantly impacting the economic feasibility and operational lifespan of batteries. A comprehensive understanding of these mechanisms is paramount for optimizing battery performance and making informed decisions regarding their utilization in EVs and other applications.

The economic ramifications of battery degradation extend beyond initial procurement and maintenance expenditures. The continuous decline in battery capacity can lead to reduced driving range, heightened charging frequency, and ultimately, the necessity for costly battery replacements. These factors can substantially affect the total cost of ownership for EV owners, potentially impeding widespread adoption. Furthermore, battery degradation poses significant challenges for emerging technologies such as bidirectional charging and energy market participation. In these scenarios, batteries are not merely used for vehicle propulsion but also for storing and discharging energy back into the grid. The constant cycling and stress imposed on the battery can accelerate degradation, requiring a careful balance between financial gains from energy trading and the battery's overall health and longevity.

Extensive research has been carried out to study the intricate mechanisms of battery degradation, with the aim of developing precise models to predict and mitigate capacity loss. These models incorporate various factors, including charging and discharging rates, temperature changes, and the chemical composition of the battery [34]. By understanding the specific mechanisms at play, researchers can devise strategies to optimize battery design, charging protocols, and overall usage patterns to prolong their lifespan and minimize degradation.

As presented in [35], battery degradation manifests in three primary modes: loss of lithium ions, loss of active anode material, and loss of active cathode material. These modes can be triggered by diverse degradation mechanisms, including solid electrolyte interphase (SEI) formation, lithium plating, and electrode particle cracking. The SEI layer formed on the cathode acts as a barrier to ion transport, impeding charge transfer and contributing to capacity fade. Lithium plating, the deposition of lithium on the cathode surface, can adversely affect battery performance and safety [26]. The movement of lithium ions within the battery also induces stress on the active anode and cathode, leading to particle cracking, which further accelerates degradation. The influence of electrode particle cracking on battery degradation is notably dependent on the specific type of electrolyte employed. While detrimental in cells with solid electrolytes, it can be advantageous for cells utilizing liquid electrolytes, as highlighted in [36].

Furthermore, external factors such as driving and charging patterns significantly influence battery ageing. Jafari et al. [37] investigated the impact of these factors on battery performance, revealing that driving styles substantially affect battery degradation, whereas the type of charging equipment used has a less impact. Aggressive driving behaviors, such as rapid acceleration and hard braking, can accelerate battery ageing due to increased stress and heat generation. The study by Jafari et al. [37] also emphasized the importance of active thermal management in mitigating battery degradation. By regulating the battery's temperature, active thermal management systems can prevent excessive heat buildup, a known catalyst for accelerated ageing. This finding underscores the necessity of integrating effective thermal management strategies into EV design to ensure optimal battery performance and longevity.

B. BATTERY AGEING FACTORS

The aforementioned battery degradation mechanisms are primarily triggered by three key parameters: temperature, charging/discharging current, and depth of discharge (DoD). Due to their inherent electrochemical properties, lithium-ion batteries exhibit optimal performance within a moderate ambient temperature range of 10–25 °C [26]. Extensive research (see [26] and [38] and references therein) has demonstrated that EV range is significantly curtailed in cold temperatures due to a substantial increase in internal battery resistance and a concomitant decrease in storage capacity. Furthermore, the energy required for cabin and battery thermal management further diminishes driving range.

In [39], it is shown that battery cycle life begins to decline when temperatures exceed 25 °C, with an accelerated reduction observed at 50 °C. Regions such as Canada, the Nordic countries, and the U.K. are particularly affected by the adverse effects of low temperatures. Despite global warming trends, the U.K. experienced 45 days with sub-zero temperatures in 2023, reaching a minimum of −16 °C. Capacity loss can reach up to 32% at −10 °C and 44% at −20 °C [40]. Given that a typical battery comprises multiple cells, each potentially experiencing varying temperatures, thermal distribution becomes a critical factor. Vidal et al. [40] recommend maintaining a temperature differential below 5 °C between cells to mitigate accelerated capacity fade caused by significant temperature variations.

Charging current also plays a pivotal role in battery degradation. Research has consistently demonstrated that elevated charging currents expedite the increase in internal resistance (the resistance encountered by ions during movement through the electrolyte), leading to accelerated capacity loss [39]. This phenomenon is primarily attributed to high C-rates introducing power that surpasses the rate of chemical reactions within the battery [41]. Elevated SoC levels can indicate overcharging, which can damage the battery. Both excessively high and low DoD/SoC values adversely affect battery health. To minimize these effects, manufacturers incorporate protective buffers at both ends of the battery's operational range, resulting in a theoretical DoD/SoC exceeding the actual usable capacity. Fig. 4 illustrates the typical regions of an EV battery, with red regions reserved for battery protection. Daily charging typically utilizes the dark blue region (up to 80% SoC), while the green region is reserved for long trips. It is noteworthy that, over-the-air software updates can modify these ranges, as demonstrated by Tesla's 2019 update, which reduced the top range for some owners to enhance battery longevity [42].

The third degradation-related factor is the battery charging current. There are two primary methods to assess the impacts of charging current. The first method is based on lab testing of individual battery cells. In [43], an EV battery cell was cycled at different C-rates (from 1.25C-rate to 10C-rate) and it was shown that the cycle life of the battery was reduced from 2950 cycles at 1.25C-rate to 414 cycles at 10C-rate charging. Second method is non-intrusive monitoring of actual EV batteries via onboard diagnostic tools. In this method, EVs are subject to frequent charging rate (e.g. 70% of the charging are DC) and the results are often compared against slower AC charging. In [44], four identical EVs (24 kWh, LMO battery) were instrumented with data loggers for measurement of battery degradation testing in different test tracks (lab, road, etc.). Two EVs were only charged by AC (Level 2 (6.6 kW)) and the

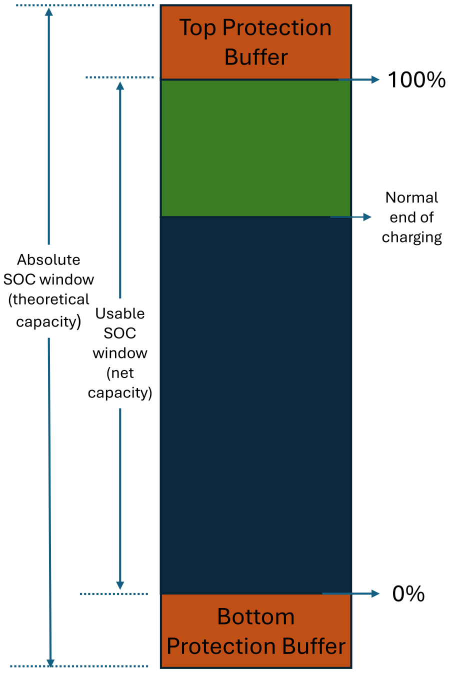

FIGURE 4. **Different regions of an EV Battery for protection and propulsion [33].**

others were charged by 50 kW DC charging. The results show that DC charging has further reduced the battery lifecycle by another 3–7% after 50000 miles of testing. It is noteworthy that the fast DC charging only corresponds to 2.1C-rate and the impacts of higher charging rates is often limited by the battery management unit of the vehicle. For instance, the maximum C-rate of Renault Zoe ZE50 R135 (maximum charging rate 41 kW DC) is less than 1, while the C-rate of Tesla Model S is 1.5 (maximum charging rate 140 kW DC) [45].

C. CYCLE AGEING

Cycle ageing, a dynamic process occurring during charge and discharge cycles, results in capacity fade, which is strongly correlated with depth of discharge (DoD) and C-rate. In addition to factors commonly cited in the literature, such as temperature and charge/discharge rate, other factors like charging strategies, dwell time at high and low states of charge (SoC), and current ripple also influence cycle ageing [46]. An empirical study presented in [47] quantifies cycle ageing using full equivalent cycles (FEC), demonstrating that battery capacity loss per FEC is dependent on both battery temperature and C-rate and is given as

$$L_{\text{cycle}}(\%) = (x_1T^2 + x_2T + x_3)exp((x_4T + x_5) \times C_{\text{rate}}) \times x_6N_{\text{FEC}}, \tag{1}$$

where the T denotes the temperature and polynomial coefficient values and units have the following values; $x_1 = 8.851 \times 10^{-6}\ 1/(K^2/Ah)$, $x_2 = -5.102 \times 10^{-3}\ 1/(K.Ah)$, $x_3 = 0.7589\ 1/Ah$, $x_4 = -6.7 \times 10^{-3}\ 1/K(C - rate)$, $x_5 = 2.344\ 1/(C - rate)$ and $x_6 = 1.5\ Ah/Cycle$. For a 1.5 Ah cell, the temperature reliance of the L_{cycle} is established empirically per Ampere-hour in [48]; this is normalised by multiplying by 1.5 Ah/cycle [49]. The results show that the deterioration per FEC is more significant when C_{rate} exceeds one. It is noteworthy that the literature presents multiple studies with empirical and semi-empirical studies on cycle and calendar ageing with varying system parameters (e.g. SoC, DoC, Temperature, C-rate) for different battery chemistry types. Interested readers could refer to Table 3 of [50] for a more comprehensive list.

TABLE 3. **Ageing Parameters for Different Battery type [51]**

		Calendar			Cycle	
j	Chemistry	X	Y	Z	A	B
1	LFP	6.02E-06	1.35E-05	1.85E-05	–4.72E-05	9.62E-05
2	LMO	6.81E-05	4.02E-05	1.63E-05	–1.21E-04	4.01E-04
3	NMC	8.07E-06	3.41E-06	2.83E-05	–4.05E05	1.01E-04
4	LTO	3.03E-06	2.81E-05	5.02E-06	–1.57E-05	4.40E-05

Gong et al. [52] conducted experimental testing on actual batteries (Samsung 35E model) for three distinct V2G services in European energy markets: frequency containment reserve, automatic frequency restoration reserve, and intraday market trading. Their findings reveal that V2G events accelerate battery degradation by an additional 3.09% over 20 months. In all V2G scenarios, weekly driving energy is assumed to be approximately 200 kWh, while the energy throughput for V2G and subsequent EV recharging slightly exceeds 250 kWh. This paper employs the following cycle ageing model:

$$L_{cycle} = A \cdot (\overline{V} + D)^2 + B + C \cdot \overline{DOD}, \tag{2}$$

where the parameters are as follows $A = 1.233 \cdot 10^{-4}$, $B = -9.729$, and $C = -0.148$. $\overline{SOC}$ and $\overline{V}$ denote the mean SOC and mean voltage over a certain period.

D. CALENDAR AGEING

Calendar ageing, which occurs when the battery is not in use, is primarily characterized by capacity loss due to the growth of the solid electrolyte interphase (SEI). While SEI formation leads to permanent capacity loss, the loss or gain associated with the Passive Anode Effect (PEA) is reversible, as explained in [53]. Research in [47] highlights the significant influence of both temperature and SoC on capacity loss resulting from calendar ageing. In [52], the authors conducted laboratory testing and developed a calendar ageing model with SoC and temperature as primary inputs:

$$\alpha_{calendar} = (X \cdot \overline{SOC} + Y) \cdot e^{(Z/\overline{T})}, \tag{3}$$

where $\overline{T}$ and $\overline{SOC}$ denote average temperature and state of charge, respectively. In (3), other parameters are obtained from polynomial fitting and have the following values: $X = 5.663 \cdot 10^5$, $Y = -2460$, and $Z = -16.08$. Moreover, in line cycle ageing formula (2), the total degradation can be written as

$$Cap_{act}/Cap_{nom}(t) = 1 - \alpha_{calendar} \cdot t^{0.75} - \alpha_{cycle} \cdot (Q(t))^{1/2}. \tag{4}$$

The term $1 - \alpha_{calendar} \cdot t^{0.75}$ refers to the ratio of remaining capacity to nominal capacity that represents the fit of time dependency, where $\alpha_{calendar}$ is the stress factor. The term $1 - \alpha_{cycle} \cdot (Q(t))^{1/2}$ refers to the ratio of remaining capacity to nominal capacity that represents the fit of charge dependency, where α_{cycle} is the stress factor. Therefore, $Cap_{act}/Cap_{nom}(t)$ is the ratio of actual capacity and nominal capacity under the combined effect of calendar ageing and cycle ageing.

Chemistry-dependent ageing models (both cycle and calendar) are presented in [51]. In this study, temperature (20 °C) and C-rate (≤ 1) is assumed to be constant. The generic formula for cycle ageing (per day) for chemistry type j is written as

$$L_{\text{cycle}} = A_j \cdot DoD_j^2 + B_j \cdot DoD_j. \tag{5}$$

There are four different battery types, hence, j can take values between 1 and 4. Note that the unit of the cycle ageing is percentage of capacity lost in one cycle. Similarly, the calendar ageing (capacity lost from idleing in one day) is written as

$$L_{\text{calendar}} = X_j \cdot SoC_j^2 + Y_j \cdot SoC_j + Z_j. \tag{6}$$

The parameters for the ageing functions for four different chemistry types are given in Table 3.

E. IMPLICATIONS FOR THE EV RETAILERS

One of the major challenges for EV retailers is to host EVs parked for a certain period. In the U.K., the average time to sell a vehicle is 40 days [54]. Depending on the outdoor temperature and SoC levels, EVs will experience calendar ageing. For instance, assuming the vehicle is kept under mild weather conditions with 50% SoC, then the associated 40-day calendar ageing for an NMC battery (using (6)) would be

$$\begin{aligned} L_{\text{calendar}} &= (8.07 \times 10^{-6} \times 0.5^2 + 3.41 \times 10^{-6} \\ &= \times 0.5 + 2.83 \times 10^{-5}) \times 40 \times 100\% \\ &= 0.1132\%. \end{aligned}$$

On the other hand, if the average temperature is within sub-zero temperatures, the implications could be more severe. Ref. [54] calculated the actual calendar ageing for a 40-day period starting from late November to mid-December and showed that the calendar ageing could be as high as 3.7%. For EV retailers, managing EVs until they are sold to a customer is a challenge. One solution could be to use heated spaces for certain battery types that are more vulnerable to outdoor temperatures or keep them connected to a charger and use battery heating for certain times of the day [26].

IV. EV CHARGING INFRASTRUCTURE

EV charging hubs are envisioned to host diverse sets of uni- and bi-directional chargers with varying charging speeds to serve the general public and participate in energy markets. This section provides an overview of current charging technologies and relevant industry standards.

EV charging technologies can be classified into two categories: wired (conductive) and wireless (inductive). Wireless charging employs a charging pad and magnetic resonance to generate an electromagnetic field for power delivery. When a receiver coil under the car aligns with a coil in the charging pad, the receiver captures the energy and transfers it to the EV's battery. While similar technology exists for charging smartphones, EV systems require a separation of approximately 0.25 meters for effective operation [55]. In principle, wireless charging could alleviate concerns about battery cost, weight, and maintenance complexity. Its potential for automation makes wireless power transfer a promising technology for future autonomous EVs [56].

However, wireless charging faces two main challenges. First, charging speeds are limited, typically below 11 kW. Although the Society of Automotive Engineers (SAE) has published a wireless charging standard for speeds up to 11 kW to ensure interoperability and performance [57], no standards exist for higher charging rates. This limitation renders wireless charging unsuitable for bi-directional applications. Second, the high cost and limited availability of wireless chargers deter potential EV buyers. Due to these constraints, this discussion will primarily focus on advancements in wired charging technologies.

Conductive charging is the predominant method for charging EVs, owing to its reliability, affordability, and ability to deliver high charging power supported by established industry standards. This method utilizes a wall outlet or EV charging station, along with a conductive cable, to transfer energy from the grid to the EV. By the end of January 2024, the U.K. had 53,677 installed public electric charging points [58], representing a 45% increase from January 2023. With the rapid development of electric vehicles, charging performance has emerged as a crucial factor influencing consumer purchasing decisions. Conductive charging can be categorized into two types: AC and DC charging. Fig. 5 provides an overview of AC and DC charging, showcasing representative chargers and sockets. Subsequent sections will delve into a more detailed analysis of these charging types. Notably, bi-directional charging can occur in both AC and DC forms, with the relevant technical details presented in later sections.

A. AC CHARGERS

In AC charging, the AC power supplied from the main electric grid is converted to DC form by the EV's onboard charger. Therefore, the AC charger's rate depends on the onboard charger's capability, which, depending on the vehicle type, accepts single- or three-phase power at 16 A or 32 A [61]. In light-duty vehicles or electric trucks, the AC charging rate can reach up to 43 kW (400 V, 63 A, three-phase) [62]. Onboard chargers, being power electronic devices, impact the cost of EVs. Hence, AC charging rates are generally slower than DC charging, which is supplied by an external charging unit.

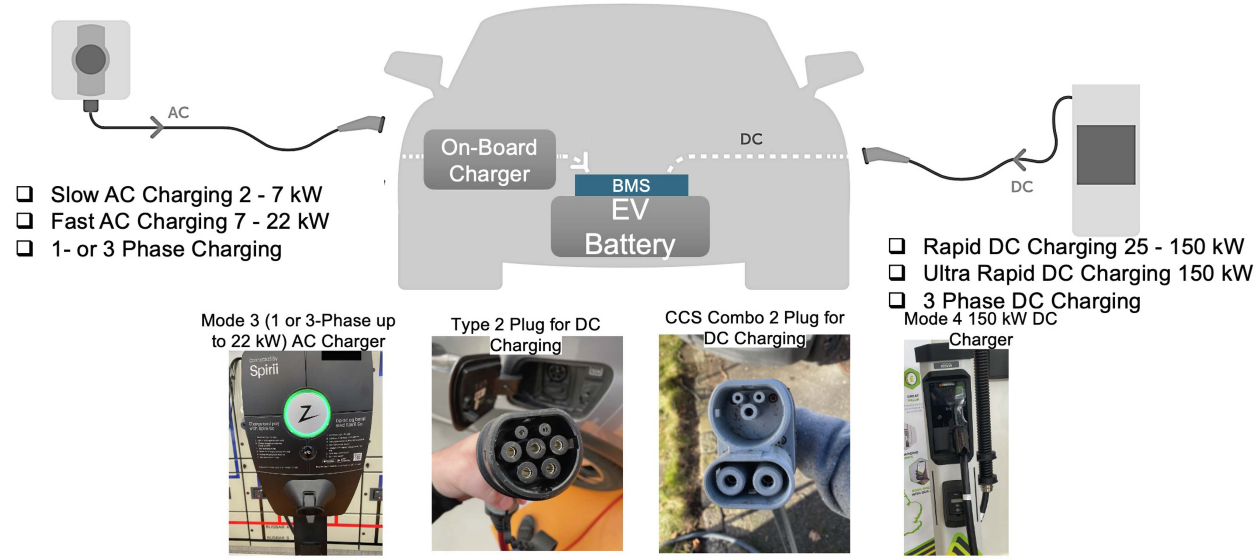

FIGURE 5. **Overview of AC and DC charging and samples of electric vehicle supply equipment. All photos are courtesy of the authors.**

The AC charging rates of some popular EVs can be calculated as follows. Most Renault Zoe models accept three-phase 32 A charging, corresponding to 3 (# of phases) × 230 V × 32 A = 22 kW. Similarly, the Tesla Model Y accepts a three-phase 16 A charging rate, equating to 11 kW of charging power. Most Nissan Leaf models can be charged with single-phase 32 A current or 3.6 kW power. It is important to note that some losses occur during AC to DC conversion, resulting in slightly lower actual stored energy compared to these calculated values. A comprehensive list of vehicle charging rates can be found in [63].

AC charging offers several advantages, including ease of installation and access, particularly at residential units, high stability, and greater affordability compared to DC charging. However, AC charging is characterized by lower power ratings and longer charging durations [60]. Consequently, it is primarily used for domestic, workplace, and street parking, where drivers can leave their vehicles parked for extended periods. The installation rate of AC chargers surpasses that of DC chargers. As of 2024, over half of the public chargers in the U.K. were AC chargers with ratings below 7 kW [64], and a similar trend is observed globally in regions with high EV adoption rates. The United Kingdom has one of the highest levels of home charging access at 93%, with over half being smart chargers. This high percentage is partly attributable to the U.K. being the first nation to introduce smart charge point regulations, coupled with a large proportion of early EV adopters having homes suitable for charger installation [65]. It is noteworthy that all currently available public AC chargers are unidirectional, as bidirectional chargers are confined to pilot trials and not yet publicly accessible.

Well-established industry standards govern AC charging. In the U.K. and Europe, the relevant AC charging standard is based on IEC 61851-1 [66]. This standard defines three modes for AC charging, each with increasing functionality and safety features (details provided in Table 4). Modes 1 and 2 deliver AC power from a wall socket to the vehicle's onboard charger, typically taking over 8 hours to charge a typical EV. Due to the lack of protection and direct contact with electrical outlets, Mode 1 is restricted in many countries, including the U.K., Germany, and Denmark. Mode 3 (AC) utilizes a dedicated charger to supply the EV's onboard charger, making it widely adopted for public chargers providing up to 22 kW AC power.

In North America, the AC charging stands are different than the European standards given above, as the nominal voltage levels are lower (e.g. 120 V in North America versus 230 V in U.K. and Europe) [67]. The North American AC charging rates are as follows:

- *Level 1:* Single phase AC charging 120 V, 1.44 kW charging rate.
- *Level 2:* Single or three-phase AC charging, typically at 240 V, up to 7.2 kW charging rate.

The specifications in Japan, China, and other major markets vary due to constraints and regulations of local electricity networks. Table 5 presents the specifications of AC charging sockets across different countries. Note that the same plugs (SAEJ11772 and Mennees (Type2) are also used for bidirectional AC power flow ([68], [69]).

B. DC CHARGERS

DC fast-charging (also referred to as DC rapid charging in the U.K.) stations can charge an EV significantly faster than common AC charging rates. DC charging networks facilitate long-distance travel and high mileage usage. They are considered essential to support EV adoption for owners who lack access to dedicated chargers [15].

DC fast charging bypasses the limitations of onboard chargers and AC/DC conversion by directly supplying DC power to the battery, thereby substantially increasing charging speed.

TABLE 4. IEC 61851 EV Charging Modes Used in the U.K. And Europe [59]

Mode	Current	Infrastructure	Power level	Applications
Mode 1	AC	Non-dedicated circuit and socket-outlet non in-cable control box	3kW for residential 7.4kW for industrial	Not recommended
Mode 2	AC	Non-dedicated circuit and socket-outlet with in-cable control and protective device	3kW for residential 7.4kW for industrial	Suitable for modest charging requirements
Mode 3	AC	Dedicated charging system and dedicated outlet multiple functions incorporated in the charge point	up to 50kW	Suitable for public/workplace/commercial best option for BEVs home charging
Mode 4	DC	Dedicated charging system and dedicated outlet with DC output	over 100kW	Not suitable for home but applicable for highways, charging hubs

TABLE 5. Overview of AC Charger Sockets for Different regions [60]

	Japan North America SAEJ1772 (Type 1)		Europe Mennekes (Type 2)		China GB/T		All Markets Tesla (NACS)	
Charger Type	Level 1	Level 2	Mode 1	Mode 2-3	Mode 2	Mode 3	Mobile	Wall
Maximum capacity	1.9 kW	19.2 kW	4 kW	22 kW	7 kW	27.7 kW	7.7 kW	11.5 kW
Input voltage	120V 1- ϕ	240V Split ϕ	250V 1-ϕ	480V 3- ϕ	250V 1- ϕ	400V 3-ϕ	120/240V 1-ϕ	208/250V 3-ϕ
Current rating	16 A	80A	16A	32A	16A	32A	16/32A	48A

TABLE 6. Overview of DC Charger Sockets for Different regions [60]

Specification Charger	Japan CHAdeMO	USA CCS1	Europe CCS2	China GB/T
Maximum capacity	50 - 400 kW	150 -350 kW	350 kW	60 - 237 kW
Input voltage	50 - 1000 V	200 - 1000 V	200 - 1000 V	250 - 950 V
Current rating	400 A	500 A	500 A	250 - 400 A
Bidirectional	Yes [70]	Yes [70]	Yes [71]	Yes [72]

TABLE 7. Electrical Characteristics of Various DC Fast Chargers (Adopted from [73])

Manufacturer **Model**	**ABB** Terra 53	**Tritium** Veefil-RT	**PHIHONG** Integrated Type	**Tesla** Supercharger	**EVTEC** Espresso&charge	**ABB** Terra HP
Power	50 kW	50 kW	120 kW	135 kW	150 kW	350 kW
Supported protocols	CCS Type 1 CHAdeMO 1.0	CCS Type 1 & 2 CHAdeMO 1.0	GB/T	Supercharger	SAE Combo-1 CHAdeMO 1.0	SAE Combo-1 CHAdeMO 1.2
Input voltage	480 Vac	380-480 Vac 600-900 Vdc	380 Vac ± 15% 480 Vac ± 15%	380-480 Vac	400 Vac ± 10%	400 Vac ± 10%
Output voltage	200-500 V 50-500 V	200-500 V 50-500 V	200-750 V	50-410 V	170-500 V	150-920 V
Output current	120 A	125 A	240 A	330 A	300 A	375 A
Peak efficiency	94%	≥92%	93.5%	91%	93%	95%

The charging time varies depending on factors such as battery size and charger output, but many vehicles can reach an 80% charge in about an hour or less using current DC fast chargers [62]. DC charging offers higher voltage and current levels compared to AC charging, delivering 4 to 10 times the maximum power [74]. Furthermore, DC charging is the preferred option for light-duty vehicles, electric buses, and other heavy-duty vehicles used for transportation [74].

Table 6 summarizes the various DC charging sockets used in different countries, highlighting the significant increase in charging currents to achieve high charging powers. Moreover, bidirectional DC charging is available in all regions to support various V2X services. Table 7 presents a detailed overview of widely used DC chargers. State-of-the-art DC fast chargers convert three-phase AC voltage, up to 480 V, into the required DC voltage through two power electronics conversion stages. The first stage involves AC/DC rectification with power factor correction (PFC), converting the three-phase AC input voltage into an intermediate DC voltage. The second stage is DC/DC conversion, which regulates the intermediate DC voltage to the specific level needed for EV charging.

It is important to note that the EV charging speed depends not only on the fast charger's power but also on the car battery's capacity, chemistry type, and state of charge when

TABLE 8. Comparison Between AC and DC Chargers

	AC Charger	DC Charger
Location of Conversion	DC Conversion is done inside the EV	DC Conversion is done inside the charging station (outside the EV)
Charger Location	Typical for home and public charging	Mostly found along highways or charging hubs
Charging Curve	Charging curve is a straight line	Degrading charging curve
Impact on Battery	Gentle to the electric car's battery	DC fast charging heats up the batteries, slightly degrades over time
Cost	More affordable ($\leq$1000 USD)	Expensive to install ($\geq$10000 USD)
Size	Has compact size	Usually larger than AC chargers

plugged in. Currently, most mainstream EVs on the road have a maximum charging rate of 150 kW or less, with many limited to 50 kW or 100 kW. Consequently, the exact charging time varies between vehicles. For example, the Renault Zoe (2020 onwards) has a maximum DC charging rate of 43 kW, while the Tesla Model Y can be charged at 175 kW. A comprehensive list of maximum DC charging rates can be found in [12]. Table 8 summarizes the comparison between AC and DC charging options presented in this section.

C. BI-DIRECTIONAL CHARGERS

Bidirectional chargers facilitate the transformation of EVs into mobile energy storage units, capable of injecting electricity back into the power grid to provide various V2X services, as detailed in Section II-B. Vadi et al. [75] outline the diverse energy transfer ranges associated with these interactions, with V2H exhibiting the lowest power level and V2G the highest. To achieve DC/AC power transfer, converters are necessary both onboard the EV and within the charging infrastructure. Acharige et al. [60] provide a comprehensive analysis of the technical distinctions between unidirectional and bidirectional power flow, encompassing switch types, control systems, services, and safety considerations. However, bidirectional charging technology is still in its developmental stages, with limited availability across EV brands. Currently, less than 10% of EV models offer V2X capabilities. For a detailed exploration of various bidirectional power electronics topologies, readers are encouraged to consult [76].

While the integration of bidirectional charging presents numerous potential benefits to the power grid, these advantages may not always scale proportionally with the technology's penetration. A prior study conducted within the U.K. context reveals that the maximum peak demand reduction is achieved when approximately 10% of households utilize EVs, with this benefit diminishing to zero as EV ownership reaches 100% household penetration [77]. It is crucial to acknowledge that, as given in [78], bidirectional EV connections to the grid can introduce disturbances and harmonic components through synchronized converters, potentially disrupting charging and discharging processes. This potential adverse impact must be carefully considered when quantifying the overall V2G potential. Although bidirectional chargers have not yet been widely integrated as standard features in EVs, the increasing prevalence of such chargers in newer models, like the Nissan Leaf, is expected to coincide with rising EV adoption rates [79].

TABLE 9. Existing Bidirectional chargers [70], [80]

Charger	Maximum PowerRating (kW)	V2X
Wallbox Quasar	7.4 (charge), 6.8 (discharge)	V2H, V2G
Highbury	7 (1-ϕ), 11 (3-ϕ)	V2H
Emporia	11.5	V2X
Fermata Energy FE20	20	N/A
Delta	11 (charge), 7.2 (discharge)	V2X
Autel Maxicharger	12	V2X
Enphase	4 to 5	V2H, V2G
SolarEdge	12 (charge), 24 (discharge)	V2H, V2G
Ford Charge Station Pro	19.2	V2H

Abbreviations: V2Z: Vehicle to Everything, V2H: Vehicle to Home, V2G: Vehicle to Grid.

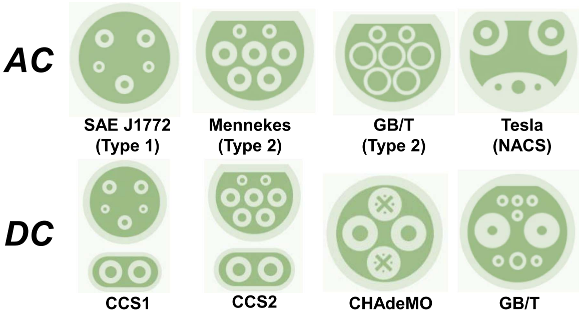

FIGURE 6. Different AC and DC charging connectors [81].

Table 9 presents announced bi-directional chargers in the market. Among all of the chargers listed in the table, some of them are available while others still haven't been released. To be specific, Emporia, Emphase, and SolarEdge are expected to be released in the market in 2024, and Autel Maxicharger's release date is still unknown. The price range of different bidirectional chargers is very wide. For example, among all the accessible prices (2024 figures), Wallbox Quasar costs from £3200 up to £5500, while Emporia only costs £1200 [70]. While it is true that each charger's performance varies, the cost would still be a decisive factor influencing their market acceptance in the future.

D. CHARGER SOCKETS

1) AC CHARGER SOCKETS

In the current EV market, two major AC charger connectors are Type 1 and Type 2 as illustrated in Fig. 6. Type 1 is a five-pin single-phase plug used in North America and Japan, while Type 2 is a seven-pin three-phase plug used in Europe

(Mennekes) and China (GB/T). Conversion between these two types can be achieved using a charger adapter, as shown in Fig. 6. Both Type 1 and Type 2 chargers are defined by the IEC 62196 standard, an international standard encompassing EV conductive charging, including plugs, sockets, vehicle couplers, and inlets [66] (IEC refers to the International Electrotechnical Commission). Type 1, utilized in the North American market, is also defined by the SAE J1772 standard, a North American standard established by SAE International (formerly the Society of Automotive Engineers). Tesla employs its proprietary charger connector, defined by the North American Charging Standard (NACS). Since the NACS Tesla charger connector supports both AC and DC charging, it will be further discussed in the following section.

2) DC CHARGER SOCKETS

Three major DC charger connectors are CCS, CHAdeMO, and GB/T. CCS, including CCS1 and CCS2, also shown in Fig. 6, stands for Combined Charging System. The CCS1 connector has 6 pins and is widely used in North America, while the CCS2 connector has 9 pins and is dominant in European markets. Three additional pins of the CCS2 connector enable more advanced communication between charging equipment and EVs. However, CCS1 is considered more stable and better suited for extreme weather conditions [82]. Competing with CCS is CHAdeMO, which was developed in Japan and remains the most popular connector in the Japanese market to date. GB/T is the standard used in mainland China.

As previously mentioned, Tesla's charger can provide both AC and DC charging. Compared to other connectors, Tesla's is lighter and easier to use, but it comes at a higher cost and does not yet offer bi-directional charging functionality. Although non-Tesla vehicles currently require an adapter to charge with Tesla's connector, some automakers have announced plans to adopt the NACS starting from 2025, suggesting a potential expansion of Tesla's market share in the future [83].

E. BIDIRECTIONAL ONBOARD CHARGERS

As previously discussed, onboard chargers (OBCs) integrated into most EVs are crucial for enabling bidirectional charging, which allows reverse power flow. These chargers give EV owners access to the vehicle's large battery capacity for uses beyond transportation. A typical OBC consists of a two-stage power converter: the first stage handles rectification and power factor correction (PFC) to comply with grid power quality standards, while the second stage is a galvanically isolated DC-DC converter that supplies the battery with the necessary charging voltage and current.

The growing trend towards bidirectional chargers in the EV market presents new challenges for OBC design. The automotive industry has stringent requirements regarding size, weight, and packaging. Additionally, frequent charging and discharging necessitate high-efficiency conversion to minimize power losses. Bidirectional converter topologies often require additional components or different selections, such as transistors instead of unidirectional diodes. Therefore, designing cost-effective bidirectional chargers is essential for their widespread adoption in the EV market.

There is a growing body of literature on the design of bidirectional onboard chargers [84]. The power rating of most bidirectional OBCs is 6.6 kW, while the power range varies from 3.7 kW to 22 kW. Similarly, the most common voltage level is 400 Vdc, in line with EV battery packs, and the literature includes new OBCs for higher battery packs, such as 700 V [85] and 800 V [86]. Lastly, the reported efficiencies hover between 94.7% and 99% [84].

F. NOVEL POWER SYSTEM ARCHITECTURES FOR V2G

The concept of the active distribution grid was introduced over a decade ago to facilitate the efficient management of EV charging and V2G operations [87]. Typically, the active distribution grid is divided into several autonomous subsystems that possess self-management capabilities and can collaborate to ensure the grid operates in a coordinated and economically efficient manner. However, there has been limited research addressing the specific characteristics of power architectures in V2G operation studies. For instance, Ref. [88] discusses the importance of the voltage profile in an AC distribution campus grid when designing V2G dispatching algorithms, noting that coordinating EV charging and discharging behaviors can help mitigate voltage overrides at certain distribution nodes. Additionally, Ref. [89] highlights that low voltage issues commonly arise at the end of radial AC feeders due to high-power charging.

In [90], we develop a cyber-physical co-modeling approach to provide foundational insights into the Internet of Smart Charging Points, where local controllers are positioned near EVs) and are coordinated with one another. From an energy dispatching perspective, a hierarchical V2G scheduling method is implemented in a distributed manner, breaking down the optimization problem into several sub-problems. Additionally, parallel computing is utilized within the V2G framework to expedite the solution process. Furthermore, voltage regulation is performed near the energy coordinator using high-performance computing, rather than relying on the local controllers.

V. CASE FOR HEAVY-DUTY ELECTRIC VEHICLES (HDEVS)

Heavy-duty trucks (specifically, Class 7 and 8 trucks with a gross vehicle weight exceeding 26,000 pounds) account for 19% of total emissions in the U.K. and 15% of the overall energy consumption and greenhouse gas emissions in the U.S. transportation sector. The operational costs in commercial heavy-duty trucking are a significant concern, making heavy-duty electric vehicles (HDEVs) an appealing alternative due to their lower maintenance requirements, which reduce costs and downtime, and their lower fuel expenses, thanks to more efficient powertrains and affordable electricity. Fuel costs alone represent half of the total cost of ownership for Class 8 diesel trucks [91]. However, HDEVs are equipped with 800 V battery packs (as opposed to the 400 V packs used in light-duty EVs) and typically require higher charging power. Therefore, this section provides an overview of 800 V batteries, the charging impacts of HDEVs, and their potential roles in Vehicle-to-Grid (V2G) markets.

A. 800 V BATTERIES

Because of the substantial traction power demands, heavy-duty electric vehicles–such as Class 8 trucks, buses, and off-highway vehicles like mining haul trucks–are ideal candidates for adopting 800 V battery systems. At elevated power levels, the advantages of reducing cable size and minimizing conduction losses become more pronounced compared to the lower power levels typically seen in passenger vehicles. Additionally, the ability to achieve faster charging rates is directly linked to daily productivity in industries such as long-haul transportation, public transit, and mining, offering a further economic incentive to shift towards 800 V powertrains. For instance, current mining haul trucks operate with a nominal battery voltage of approximately 670 V [92], as a 400 V system would be inefficient for the required power levels and would lead to longer charging times, significantly impacting productivity in mining operations. Although several manufacturers are working on electric Class 8 trucks, specific details on powertrain voltages are still not widely disclosed. It is highly recommended that vehicle and truck designers give serious consideration to transitioning to 800 V powertrains, especially as more components become available due to the ongoing shift in the passenger vehicle sector [93].

Two of the primary challenges for light-duty EV adoption are limited driving range and lengthy recharge times. Ultra-fast charging can alleviate both of these issues. However, for typical 400 V battery EVs, the charging rate is constrained by the practical limitations of cable size needed to handle the charging current. To achieve ultrahigh charging rates of 350 or 400 kW, 800V EVs present a promising alternative and have been recently introduced in certain EV models, such as the Porsche Taycan. Nevertheless, designing an 800 V EV requires careful re-evaluation of all electrical systems.

Beyond the benefits of ultrafast charging, an 800 V battery EV offers additional advantages over a conventional EV equipped with a 250 V–450 V battery. In [94], the advantages of 800 V EVs are explored, including faster charging under given battery current limits, lower electrical losses due to reduced I^2R losses, and smaller motors and wiring sizes resulting from lower current requirements.

While higher battery pack voltage is desirable for boosting maximum charging power, it introduces additional complexity [93], [94]. An 800 V battery pack necessitates twice the number of series-connected cells, thereby requiring twice as many voltage-sensing channels in the battery management system (BMS). However, the number of current sensors, contactors, and temperature sensors would likely remain the same. The increased computational demands on BMS algorithms are necessary due to the need to monitor additional cells. Moreover, the battery pack contactors, fuses, and cables must be rated for at least 900 V for an 800 V pack, as opposed to 500 V for a 400 V pack. On the other hand, the cross-sectional area of the DC cabling that transfers power between the battery pack and the traction inverter, fast-charging port, and other high-voltage systems can be reduced in an 800 V system, leading to some reductions in vehicle mass.

B. HDEV CHARGING

While previous research has examined the effects of added electrical loads on distribution systems, particularly in the context of light-duty EVs, the consequences of charging heavy-duty EVs (e.g. vocational vehicles, off-highway vehicles, etc.) remain relatively underexplored. HDEVs are typically charged at depots owned by the fleet operator or owner [95]. The grid impacts and reinforcement requirements associated with charging depend on factors such as the vehicle's drive cycle and the duration of off-shift periods. For example, beverage, warehouse, and food delivery trucks generally have moderate vehicle miles travelled (VMT), whereas off-highway vehicles like tractors exhibit less seasonal variation in usage. Consequently, VMT and off-shift dwell-time are two critical parameters in determining the impact of HDEV charging [96].

In [95], an scheduling model is developed to optimally charge electric buses in a charging depot. In this model, the trade-off between the size of the charging depot and the size of the electric bus batteries are discussed. It was shown that as the size of the batteries increase, the charging power requirement reduces to complete the same timetable.

In [91], the charging impacts of HDEVs for three fleet types, namely beverage, warehouse, and food delivery trucks are studies with 100 kW chargers. Three different charging methods were explored. In the first one, HDEVs are immediately charged after the shift ends with 100 kW until the battery is fully charged. In the second scenario, the charging is delayed to be completely charged before the next shift starts, while the third strategy charges the vehicle with minimum power such that HDEVs is fully charged before the next shift. It is shown that the third strategy produces a more modest but still substantial reduction in peak load of nearly 40%.

Ref. [91] further explores the likelihood of distribution substation upgrades. The results indicated that the magnitude of the depot charging loads is more indicative of the likelihood for substation upgrades than is the timing. substation upgrades cost between US$400,000 (feeder breaker) and US$35 million (new substation), which take six months to four years to complete and potentially result in higher electricity costs and delayed fleet electrification.

Utilizing an extensive dataset containing over 200 million GPS records from 20,992 buses in Beijing, Ref. [97] investigates the technical, economic, and environmental impacts of converting public transport depots into renewable energy hubs. The findings indicate that integrating solar photovoltaics can reduce the grid's net charging load by 23% during periods of electricity generation and decrease the net peak charging load by 8.6%.

In [98], a methodology is proposed to model the load profile of a high-power charging station for HDEVs. The generated load profiles, incorporating various future HDEV adoption rates, are utilized to assess the impact on the power grid in a representative area in Norway. The results indicate that the regional substation's loading surpasses its rated capacity when HDEVs constitute 25% of the vehicle share and exceeds its thermal limit when this share rises to 50%.

C. HDEV AND V2G HUBS

The charging needs of HDEVs can be classified into two categories depending on daily Vehicle Miles Traveled (VMT). HDEVs with lower VMT ($\leq$ 200 miles per day) typically use charging depots, while long-haul HDEVs rely on en-route Megawatt Charging Systems specifically designed for these vehicles. For instance, the Volvo FMX Electric (up to 540 kWh, with charging at up to 250 kW) and the 65-tonne rated Scania (up to 624 kWh, with charging at up to 375 kW) are two well-known HDEV models used for long-haul travel [99].

Since en-route charging stations are primarily designed to support long-distance HDEV trips, charging hubs that host and charge short-haul HDEVs are better candidates for serving as V2G hubs. For example, the use of electric school buses for V2G applications has garnered significant interest. Given that HDEVs are equipped with 800 V batteries, high-power V2G chargers can be utilized to provide substantial discharge power. An example of this is the Nuvve DC Heavy-Duty Charging Station (RES-HD60-V2G) and the Nuvve DC Rapid HD Charging Station (RES-HD125-V2G), which are specifically designed for V2G applications, offering charging capacities of 60 kW and 125 kW, respectively [100].

In addition to electric buses, other HDEVs could be employed for V2G applications depending on their daily off-shift dwell duration and the number of operating days per year. Ref. [91] indicates that HDEVs have, on average, 14.1 hours of off-shift dwell time, which is sufficient for these vehicles to participate in V2G markets and be recharged before the next shift. Similarly, HDEVs are expected to operate 260 days per year, leaving the remaining days (e.g., weekends, holidays, etc.) available for their batteries to be used in V2G sessions.

VI. ELECTRICITY MARKETS

The previous sections presented battery, charger, and other EV-related technologies essential to studying bidirectional charging hubs. Next, a detailed analysis of how bidirectional chargers could be utilized for V2G services is presented. Therefore, a detailed analysis of the U.K.'s ancillary services is discussed. Based on actual datasets, the suitability of certain EV models for different ancillary services is presented. The methods described in this section could also be applied to regions with different energy market requirements.

Recall that V2H, V2L, V2V, and V2B services are considered behind-the-meter applications as the reverse power flow does not travel back to the main grid [103]. Therefore, our primary focus is on V2G services, which are quite critical for bi-directional charging hubs. Fig. 7 shows the battery capacity of V2G-capable EVs currently available in the market [12]. It can be seen that the average battery pack is 79.64 kWh, a promising size for an average EV to join V2G applications and still have sufficient energy to drive without charging on the same day. As will be discussed in Section VII, most of the existing demonstration studies had EVs with a capacity of 40 kWh or less. Therefore, limitations related to battery capacity will be reduced in future applications due to reduced anxiety of battery drainage with higher battery packs.

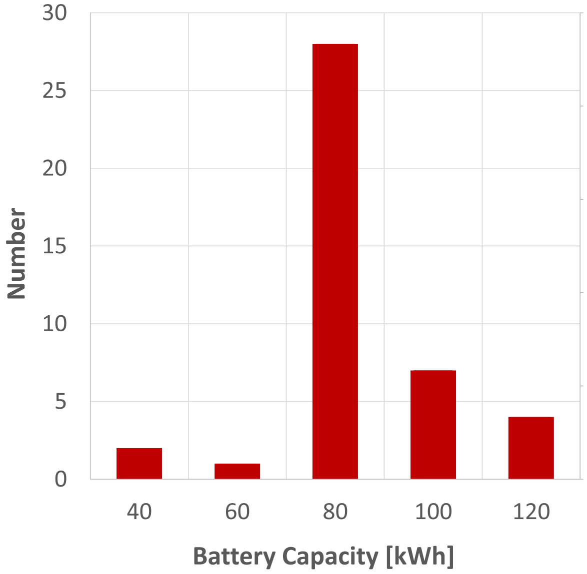

FIGURE 7. **V2G-capable EV battery capacity distribution. (Mean: 79.64 kWh Standard deviation: 13.87 kWh.)**

V2G applications have great potential in ancillary services, which are essential processes that ensure the delivery of electricity across the grid while maintaining the power system's stability, efficiency, and safety [104]. As electricity travels throughout a given region, it must be managed to balance power generation and electricity usage levels. Regulating elements like frequency and voltage is crucial to ensure that the large volumes of electricity being transmitted can be used safely in homes, businesses, schools, and hospitals nationwide. Ancillary services encompass a wide range of electrical efficiency and safety mechanisms, all focused on ensuring the power system provides sufficient output to meet demand while remaining stable. Even though there is a wide range of ancillary services, such as congestion management, voltage regulation, power quality, grid stability, and emission management, the existing literature shows that V2G applications are primarily suitable to support two types of ancillary services, namely, Frequency and Reserve markets [105], in the U.K., and their details are given as below.

1) *Frequency:* The U.K.'s power system operates at a frequency of 50 Hz. To maintain the electricity supply-demand balance, this frequency must be consistent.

TABLE 10. Summary of Technical Market Parameters of Ancillary services [101], [102]

Market type	Market name	Length of time to respond (sec.)	Length of delivery (min.)	Minimum volume (MW)	Procurement window	Aggregation Type
Frequency Response	Static Firm Frequency Response (SFFR)	30	30	1	Daily auction	Nationwide
	Dynamic Containment (DC)	0.5	15	1	Day-ahead tenders	GSP group
	Dynamic Moderation (DM)	0.5	30	1	Day-ahead tenders	GSP group
	Dynamic Regulation (DR)	2	60	1	Day-ahead tenders	GSP group
Reserve Markets	Balancing Mechanism (BM)	Defined by provider	15-min. maximum	1	60 min. ahead of real time	GSP group
	Short-Term Operating Reserve (STOR)	20 min.	120	3	Day ahead	GSP group
	Fast Reserve (FR)	2 min.	15	25	Optionally procured in real time	GSP group
	Quick Reserve (QR)	1 min.	15	1	Daily – 14:30	GSP group
	Slow Reserve (SR)	15 min	120	1	Daily – 14:30	GSP group
Flex.	Demand Flexibility Service (DFS)	7.5 hours (minimum)	30	1	Day ahead – 16:30	GSP group
	Local Constraint Market (LCM)	1 hour (minimum)	30 (minimum)	0.001	Day ahead or intraday	within Scotland near England border.

In Addition, the Full Power (Maximum Time to Full Delivery (MTFL)) Should Be Provided Within 1 Second for DC and DM and Within 10 Seconds for DR. Grid Supply Point (GSP)is the Point At Which the National Transmission Network, Operated by National Grid, Connects to Regional Distribution Networks.

Turbines and generators automatically adjust their speed to increase or decrease power output in response to demand, ensuring system stability. V2G systems can further support frequency services by dynamically charging and discharging large numbers of EVs.

2) *Reserve:* A critical aspect of ancillary services is preparedness for unexpected events. By holding back power for potential release, the network can operate with confidence, knowing that there are backup generators and other power sources, such as EVs, ready to support the system when needed.

The present paper primarily considers V2G applications for the U.K. ancillary services, while the requirements and the terminology could be different elsewhere. Table 10 presents associated ancillary services published by National Grid. The markets related to frequency regulations are static firm frequency response, dynamic containment, dynamic moderation, and dynamic regulation. Similarly, reserve markets include balancing mechanisms, short-term operating reserve, fast reserve, quick reserve, and slow reserve. In addition, V2G could also play a key role in demand flexibility services and local constraint markets. The local constraint market has recently been introduced to save overall costs for the customers on actions at the English-Scottish border (B6 boundary), which is the most constrained boundary in the Great Britain system.

Table 10 further reveals that there are three main requirements for EVs to join a specific market:

1) *Response Duration:* Depending on the market type, the response duration requirement determines the maximum delay that EVs need to respond. It can be seen that the response duration is very tight (less than a second for dynamic containment and dynamic moderation) and slightly longer for reserve markets. It is also noteworthy that the maximum time between frequency deviation occurring and delivery of the maximum power is 1 s for dynamic containment and moderation, while it is 10 seconds for dynamic regulation [107]. The work presented in [106] shows communication delay measurements taken from six different vehicles. As shown in Fig. 8, there are four different delays in EV charging:

a) t_a is the delay related to initiation of the charging process.

b) t_b is the time it takes for the EV to reach full rated charging process.

c) t_c is the time it takes to initiate ramp-down.

d) t_d is the time it takes to stop charging completely.

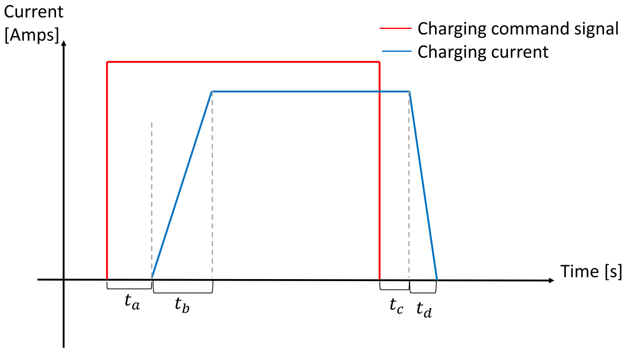

FIGURE 8. Communication delays related to EV charge initiation, ramp up/down and completing the process. [106]

Note that the delays provided above are for uni-directional charging; however, it is reasonable to assume that similar profiles would occur for bi-directional chargers [106]. Table 11 shows the testing results of six different EV models. It can be

TABLE 11. **Average Communication Delays of Onboard EV chargers [106]**

Vehicle	t_a (s)	t_b(s)	t_c (s)	t_d (s)	Ramp-up (kW/s)	Ramp-down (kW/s)
VW ID3 Pro(2023) 58kWh	2.54	1.1	0.78	0.14	10.03	78.85
Nissan Arya (2022) 87kWh	0.5	4	0.02	1.5	6.59	12.55
Nissan LEAF e+ (2022) 62kWh	3.6	1.28	0.03	0.23	5.75	5.01
Skoda Enyaq iV 60 (2021) 62kWh	2	1.2	0.68	0.1	9.17	110.4
Tesla M3 LRDM (2020) 78.1kWh	2	15	0.02	0.02	0.73	552
Renault Zoe 40 (2018) 44.1kWh	3.8	3.6	0.1	0.5	6.13	27.6

observed that the Nissan Arya has the shortest start-up delay, and the Nissan Arya, Nissan LEAF e+, and Tesla Model 3 LRDM have better performance when it comes to the ending delay. The next sections will provide a cross-examination of EV types for different ancillary services.

2) *Delivery Length:* V2G services should be able to provide contracted power during the length of this value. It can be seen that the minimum delivery length is 15 minutes; hence, the total stored energy of the V2G should be contracted power multiplied by the length of delivery (in hours).
3) *Minimum Volume (MW):* This is the minimum amount of power required to join ancillary services. For most markets, 1 MW is the minimum capacity, which indicates that V2G applications require aggregating about one hundred vehicles if 10 kW bi-directional chargers are used. It is noteworthy that it is easier for EV retailers to reach this amount when compared to other aggregators.
4) *Procurement Window:* This is the time window when applications for different markets are made.

In the next sections, the details of each ancillary services market are explained in detail, and the suitability of the EV retail business for V2G services is explained.

A. FREQUENCY RESPONSE

Frequency response is one of the most important ancillary services, and most grid operators, such as the National Grid, have a statutory obligation to maintain the grid frequency within ±0.5 0.5 Hz, that is, between 49.5 to 50.5 Hz. The control of the National Grid normally controls the system frequency within a tighter operational range of 49.8 to 50.2 Hz. It is noteworthy that the system frequency changes when the electricity supply-demand balance deviates from the ideal position. If the demand is greater than generation (e.g., loss of generation, etc.), the system frequency falls below 50 Hz. On the other hand, if the generation is greater than demand (e.g., excess wind), the system frequency rises. In this case, when the system frequency drops, depending on the rate of change of frequency (RoCoF), V2G networks inject power back into the grid or stop charging. Similarly, when the frequency is higher than the upper limit, additional EVs are charged to absorb excess generation.

As given in the previous section, different ancillary services are implemented to stabilize the system frequency within acceptable levels and help balance and restore the system when there is a contingency. Fig. 9 shows the framework of frequency control when contingencies occur, where the primary frequency response (automatically) helps contain the system frequency, and the secondary frequency response aims to (automatically and manually) restore the frequency to its nominal value [108]. Three periods throughout the post-event time are explained below [111]:

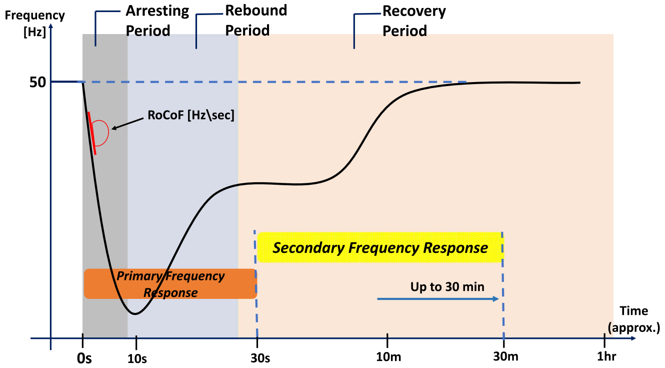

FIGURE 9. **Frequency control framework. [108], [109].**

- *Arresting Period:* The stage when the frequency drop is being arrested in case of further system collapse.
- *Rebound Period:* The stage when the frequency has been stabilized but is still lower than initial scheduled value.
- *Recovery Period:* The final stage when both frequency and reserves held for previous frequency control are restored. Frequency is at the initial scheduled value.

Among all the frequency services available in the market, Firm Frequency Response (FFR) is the traditional one, which can be divided into Static Firm Frequency Response and Dynamic Frequency Response. As a new dynamic service recently introduced by National Grid, Dynamic FFR can consistently deal with the second-by-second changes in the power system and provide primary and secondary frequency response. Static FFR is activated at a defined frequency deviation and has a slight advantage for EV penetration due to its longer response time (30 seconds) and longer delivery duration (30 minutes), compared to Dynamic Containment (DC), Dynamic Moderation (DM), and Dynamic Regulation (DR) [101].

Among all the new dynamic services in Table 10, DC is a fast-acting, post-fault service introduced in 2021, while DM and DR are both pre-fault services introduced in early 2022

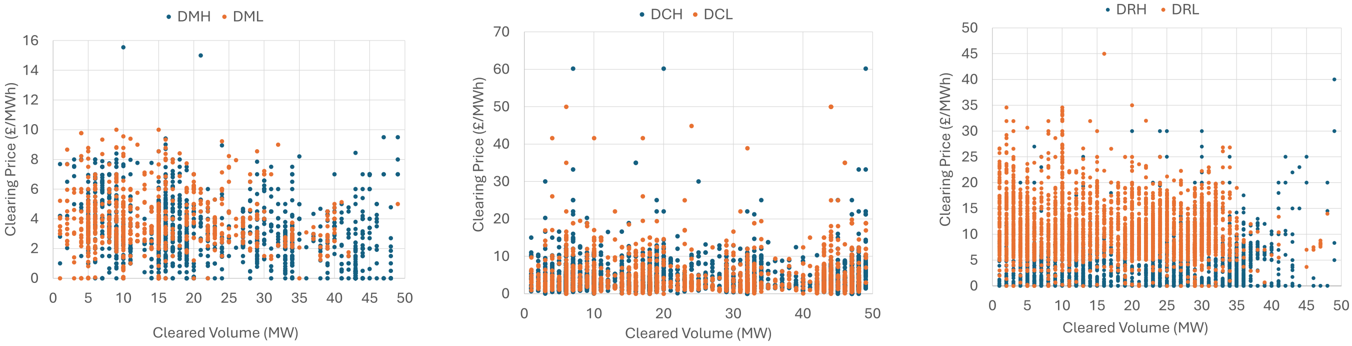

FIGURE 10. **Tesla motor's [110] winning bids to dynamic frequency markets for 2023: Dynamic containment, moderation, and regulation. H and L denote the upper and lower bounds for frequency containment (e.g., DCH is 50 Hz + 0.5 Hz and DCL is 50 Hz - 0.5 Hz), respectively.**

that allow automatic adjustments [112]. According to [112], DR has not only the longest initiation and delivery duration but also the maximum time to achieve full delivery after the frequency deviation occurs, with both DC and DM taking one second, while DR takes ten seconds.

The National Grid open data repository also provides information on successful bids for frequency services [107]. The dataset covers bids from September 2021 until February 2023 with 34 active players. Tesla Motors is one of the leading players in the U.K.'s frequency response programs, with a market share of nearly 10%. Tesla Motors uses stationary storage units to join frequency markets using their AI-based bidding technology [113]. The market volume for DC, DM, and DR is expected to exceed 1 GW per month, providing vast opportunities for V2G services. In Fig. 10, the successful daily market bids of Tesla Motors are presented.

EVs integrated into a V2G system can provide plentiful resources related to frequency response, while sophisticated scheduling structures are needed to deal with the inconsistency in the number of connected EVs. In [114], authors demonstrated that scheduled frequency response considering the uncertainty of EV plug-in times will hasten the progress of huge cost savings in the U.K.'s future power grid. Advanced control mechanisms should be applied with the implementation of the V2G system; otherwise, as indicated by the results in [115], it will have detrimental effects on the load frequency of the power system. In [116], the author mentioned that implementing their V2G primary frequency control strategy can also help to ensure the EV battery's SOC level. However, due to the EV's primary transport function, the driver's charging behavior would also rely on the electricity market price, which would constrain the EV's utilization in frequency control. Thus, the author in [116] suggested that meeting customers' requirements should be the secondary purpose of their V2G control strategy.

In Europe, the frequency containment reserve (FCR) is the service equivalent to dynamic containment. FCR involves adjusting EV charging and discharging rates to respond to real-time fluctuations in system frequency. If the grid frequency deviates by 200 mHz or more from the rated frequency, assets participating in FCR must provide their full offered power. Regulations stipulate that FCR products are provided in 4-hour blocks, and assets must be capable of delivering the maximum offered power in both directions for a minimum of 15 minutes during this period. In a V2G event supporting FCR, the requested FCR power is calculated using the following equation [52]:

$$P_t^{\mathrm{FCR}} = \begin{cases} \min\left(P^{\mathrm{Max}} \cdot \frac{f_t^{\mathrm{Grid}} - 50\,\mathrm{Hz}}{200\,\mathrm{mHz}} \cdot (1+20\%),\, P^{\mathrm{Max}}\right), & \\ & \text{if } f_t^{\mathrm{Grid}} > 50\,\mathrm{Hz} \\ \max\left(P^{\mathrm{Max}} \cdot \frac{f_t^{\mathrm{Grid}} - 50\,\mathrm{Hz}}{200\,\mathrm{mHz}},\, -P^{\mathrm{Max}}\right), & \\ & \text{if } f_t^{\mathrm{Grid}} < 49.99\,\mathrm{Hz} \\ 0, & \text{otherwise,} \end{cases} \tag{7}$$

where P^{Max} is the maximum discharge rate of a bi-directional charger (see Table 9 for typical rates) and f_t^{Grid} is the locally measured grid frequency at time t.

1) V2G ELIGIBILITY ASSESSMENT FOR FREQUENCY MARKETS

In most V2G applications, it is assumed that the system frequency is measured locally, and the vehicle is already connected to the charger. Otherwise, communication delays could be a significant issue, as works presented in [117] and [118] show that 4G communications between a control center (where frequency measurements are taken) and a typical vehicle retailer could add another one-second delay (depending on signal strength and message length). Since EVs have already been connected to a charger, the eligibility to satisfy delay requirements in Table 10 to join a frequency market is more likely.

In Table 12, the examination of EV models, with specifications presented in Table 11, for the minimum delay, power, and energy requirements is presented. In this examination, it is assumed that the fleet is uniform and only contains a single EV type. Each charger is identical and can discharge an EV at a rate of 10 kW (for the sake of simplification, efficiency losses are ignored), and EVs are assumed to be fully charged before the V2G event. In FFR, the response length is 30 seconds, so each EV model can join this event within 30 seconds and discharge for 30 minutes. Given the charger rating, there would be a need for 100 EVs to satisfy the minimum volume.

TABLE 12. Examination of V2G Applications for Various Frequency Regulation Markets for EVs With Technical Details Given in Table 11

Vehicle	Static Firm Frequency Response	Dynamic Containment	Dynamic Moderation	Dynamic Regulation
VW ID3 Pro 58 kWh	Yes (100 EVs)	No (LTR)	No (LTR)	No (LTR)
Nissan Arya 87 kWh	Yes (100 EVs)	Yes (152* EVs)	Yes (152* EVs)	Yes (100 EVs)
Nissan Leaf 62 kWh	Yes (100 EVs)	No (LTR)	No (LTR)	No (LTR)
Skoda Enyaq 62 kWh	Yes (100 EVs)	No (LTR)	No (LTR)	Yes (100 EVs)
Tesla M3 78 kWh	Yes (100 EVs)	No (LTR, MTFL)	No (LTR, MTFL)	Yes (137* EVs)
Renault Zoe 40 44.1 kWh	Yes (100 EVs)	No (LTR)	No (LTR)	No (LTR)

EVs are Assumed to Be Fully Charged and Connected to a 10 Kw Bidirectional Charger. Abbreviations (From Table 10): LTR (Length of Time to Response), MTFL (Maximum Time to Full Delivery). Fleets are Assumed to Contain a Single EV Type. Starred* Cases Represent a Partial Discharge Rate (≤10 Kw) to Comply With the MTFL Requirement of 1 Second.

The examinations for DC and DM are more complex, as the length of time to respond is 0.5 seconds, and the maximum time to full delivery (MTFL) is also one second. In this case, only fleets composed of Nissan Aryas are eligible to join the V2G markets. Note that there would be a need for 152 EVs to satisfy the 1 MW requirement because, in one second, the Nissan Arya discharge rate is 6.59 kW (see Table 11). Hence, there would be a need for 1000 MW / 6.59 kW = 152 EVs (minimum power requirement divided by the power rating of each charger). Similarly, there would be a need for 137 Tesla Model 3s to join DR services to satisfy the MTFL requirement of 10 seconds. Note that the Renault Zoe and Nissan Leaf have delays of more than 2 seconds; hence, they are not eligible to join DR market bids.

B. RESERVE MARKETS

Reserve markets (also known as balancing reserve) refer to obtainable extra energy sources by reducing either generation or demand. They enhance security when facing power demand different from the forecast. Unlike frequency response services, reserve services are instructed manually, resulting in a relatively longer response time. Reserve services can be characterized in different ways by their response time, ranging from 1 minute to 20 minutes, as given in Table 10.

Currently, the Balancing Mechanism (BM) is the dominant tool applied to balance Great Britain's power system. This mechanism is an online auction that accepts bids and offers from participants. Bids and offers can be used to provide Regulating Reserves. Short-term Operating Reserve (STOR), a contracted service of the National Grid accessible to both BM participants and non-BM participants, requires a minimum equivalent power volume of 3 MW. It adjusts the generation or demand at specific times every day, depending on the current power system situation. In other words, carrying out this service is highly dependent on the local time and season. With the integration of EVs and the V2G system to adjust EVs' charging and discharging time, a high level of information aggregation is necessary for the synchronized operation of a large number of vehicles. With the enlarged scale of EV integration, EV suitability and stringent technical requirements should be taken into consideration more. New reserve services with lower power thresholds and faster responses, such as Quick Reserve (pre-fault) and Slow Reserve (post-fault), are expected to be proposed to replace existing reserve services and adapt to the new, more flexible, and variable power system structure.

1) V2G ELIGIBILITY ASSESSMENT FOR RESERVE MARKETS

In frequency regulation, the *length of time to response* is the most critical parameter when it comes to examining the eligibility of specific EV models given in the previous section. For the case of reserve markets, this time value is at least one minute or more, hence all EVs can satisfy this requirement. Similarly, the longest *length of deliver* is 120 minutes (STOR and SR). With 10 kW bi-directional chargers, this is equivalent to 20 kWh of energy. Recall from Table 11, all EV models have battery capacities higher than 44.1Wh, therefore, this requirement is also satisfied. *Minimum volume* to join certain reserve markets could be a challenge for vehicle retailers as STOR requires 3 MW (300 EVs) and FR requires 25 MW (2500 EVs) to be eligible for these two specific markets. While the requirement for STOR seems more manageable if multiple vehicle retailer locations are aggregated. However, owning 2500 bidirectional chargers may not be practical at this stage of vehicle electrification for most EV retailers.

C. FLEXIBILITY MARKET

Flexibility services incentivize customers, including domestic, industrial, and commercial sectors, to alter or shift their electricity usage during peak load periods, thus achieving peak shaving and valley-filling. The service agreement is based on mutual cooperation and benefits between the provider and the customer, with contracted capacity and power requirements tailored to the specific zone and service window.

A study conducted in Denmark [105] categorized flexibility services into three types: natural, scheduled, and conditional. The U.K. offers a similar range of services, including the DA product, Dynamic, Secure, Restore, and Sustain which are explained below.

- *Day ahead (DA) product:* DA product is identified as scheduled utilization procured day-ahead through an auction.
- *Dynamic:* Operational utilization, refers to the non-firm product that permits customers to declare capability and set price.

- *Secure:* A product that combines DA product and Dynamic.
- *Restore:* A product that supports the restoration of the network when there's an unplanned situation, under which circumstance the flexible unit is delivered close to real-time.
- *Sustain:* A product that reduces the peak load from a flexible unit during all service windows.

The Electricity System Operator (ESO) of Great Britain successfully launched the Demand Flexibility Service (DFS) in the winter of 2022/23, attracting over 2.2 million customer sign-ups in 2023. This significant interest demonstrates customer awareness of grid flexibility challenges and the potential for rewards through participation. The increasing integration of EVs and renewable energy sources necessitates greater grid flexibility, while simultaneously enhancing the grid's capacity to leverage this flexibility. To encourage voluntary participation in flexibility markets, system operators should segment potential providers based on their driving and charging patterns. Charging flexibility can be defined as the proportion of time the charger is idle while the EV is plugged in (see [119]).

D. ECONOMIC BENEFITS

Battery is the most expensive part of an EV. Therefore, it is essential to examine the economic viability of EVs to offer V2G and other services [120]. As the number of V2G-capable EV models increase, a growing body of literature is investigating the economic evaluation of EV aggregators. The requirements and associated financial gains of V2G applications depend on the type of energy market which is presented in Section VI. In modelling frameworks, the input data include mobility behaviour (reflecting probability of being in a specific location for charging), battery capacity, battery degradation model, charger equipment cost, charging power and efficiency [121]. The literature reports wide range of economic gains for V2G applications for different regions and under different assumptions. Details of some of the reported studies are follows. In [120], a techno-economic analysis is presented in 2021 using the market prices of New York Area. It was found it is highly likely that EV aggregators operate at a loss with the price of a single battery cell unit is concerned. However, it is further discussed that with the fallen battery prices, V2G service will be profitable for both EV owners and grid operators. Meanwhile, V2G system operators should implement specific service strategies and provide rewards to help users cover their battery degradation cost [125]. Nevertheless, the decrease in battery SoH would reduce the V2G system's ability to alleviate battery degradation [126]. According to [127], some factors can be not independent and influenced by others, for instance, current rates show no impact on the capacity loss at high temperatures but are unignorable at normal temperatures. To minimize the ageing cost and ensure safety, researchers should not only understand the individual effects of each factor that can contribute to degradation but also put all factors (e.g. current rate, temperature, DOD) together and consider different scenarios. It is also noteworthy that the application of dynamic degradation cost has more benefits compared to constant degradation costs, such as the prioritization of more suitable EVs for the V2G program and a smaller range of final battery capacities for a group of EVs according to [128], tracked by the blockchain-based system proposed in this paper.

Study presented in [129] compared three options for using V2G chargers: providing frequency containment reserve, peak shaving, or a combination of both. The results revealed that combining these services was the most financially rewarding option. Over a 10-year period, this approach generated a net present value (NPV) of €19,500, significantly higher than peak shaving (€11,000 NPV) or frequency containment reserve (a loss of €21,100 NPV) offered individually. Note that the analysis assumes a € 1,000 upfront investment per charger borne by the service provider. The monetary benefits of V2G trials in the U.K. are presented in the next Section.

E. ANCILLARY SERVICES AND V2G IN CHINA

To provide a comprehensive overview of Vehicle-to-Grid (V2G) and ancillary services, this section focuses on recent efforts in China. As the largest contributor to global electricity demand, China is highly ambitious in developing EV battery technology and expanding its EV market. The existing ancillary service markets in China include day-ahead response, intraday response, real-time response, reserves, frequency regulation (FR), capacity markets, and power quality markets [130]. These ancillary services in China, based on market region range, can be divided into inter-provincial and provincial markets [131]. The types of services applied vary across different regions to address local specific demands. From a provincial perspective, frequency regulation is the most common market in some provinces, where a power spot market has been launched to replace peak-shaving [132]. The power spot market refers to a market where the price of electricity is variable, and the delivery time is also flexible. In [130], researchers also highlighted the importance of frequency regulation at the distribution level for China's new power system, supported by the establishment of renewable energy sources and Virtual Power Plants (VPP) in the future.

Although slightly later in adoption than the U.K., the USA, and Japan, there is a growing trend of V2G applications across China. The first official implementation of a V2G charging station in China was in 2020, and the demonstration of this technology entered a thriving phase in 2022. In 2022, over 77 V2G chargers were installed across five cities in China, covering four provinces [130]. In 2023, four additional V2G projects were carried out. The projects in Taizhou and Wuxi deployed 14 and 50 units of 60 kW DC V2G charging points, respectively, both investigating the potential value of providing flexibility services, such as peak-shaving [133]. In conclusion, the Chinese government has been proactively encouraging the development of V2G projects by launching large-scale trials in eastern coastal provinces and other inland cities, where the power system is more mature.

TABLE 13. Launched V2G Projects in the U.K. [122]

Project Title	Number of Charger/Enabled EVs	Charger Type	Charging Location	Services
Powerloop	135 chargers	DC	Domestic	Flexibility, Balancing Mechanism
V2GO	Unavailable	AC	Commercial Charging [123]	Frequency Response, Flexibility
Bus2Grid	30 e-buses	AC	Public Transport	Frequency Response, Flexibility
Sciurus	320 chargers	DC	Home Charging	Frequency Response
E FLEX	100 EVs [124]	Not specified	Not specified	Frequency Response,Flexibility
EV elocity	35 chargers	DC	Workplace	Flexibility

VII. LAUNCHED V2G PROJECTS IN THE U.K.

Over the last few years, a number of large scale V2G demonstration projects were carried out in the U.K. to de-risk V2G applications and pave the way wider customer acceptance. A summary of the V2G projects within the U.K. is presented in Table 13. This section briefly reviews the findings of these projects.

On the most recent concluded projects is the Powerloop, which aims to explore the V2G's potential in Balancing Mechanism and the economic values. The project included 135 participants and their charging point were linked to the National Electricity Control Centre (NECC) with no more than 1 MW combined power capacity. For all participants, a Nissan Leaf with ChADemo plug and Wallbox bi-directional charger was installed. The trial included responding to several BM market messages and focused on minimizing time delays in responding to market signals.

V2GO introduced V2G into the fleets market, due to the reason that fleets have more predicable and limited vehicle use patterns and more collective installation of charging infrastructures, which are the main challenges of real-world V2G trials. Targeting at fleet operators, the benefits of EV adoption, V2G and smart charging strategy were analysed.

Bus-to-Grid was launched in Northern London in 2021. 28 BYD ADLEnviro 400 EV, each having a 382 kWh LFP battery, are capable to return 1.1 MW capacity back to the grid. Buses were charged at 80 kW and discharged a 60 kW. Although B2G is not a concept discussed as much as V2G, planned and limited using profile and bigger battery size (higher charge/discharge rate) indicate the potential value of the electrification and bi-directional charging of public transportation. Similar to the project launched in London, trial on school bus providing grid services in Canada is currently undergoing [134].

Sciurus, the largest domestic V2G trial till 2021, after testing over 320 V2G domestic units for a year, drew the conclusion that by targeting the right customer archetypes and utilising EVs with battery sizes of 40 kWh (Nissan Leaf) and above, higher annual V2G revenue can be yielded. Among all the customer archetypes, the retired professional archetype has the highest V2G revenue. Annual per customer revenue of V2G, V2G with firm frequency response, and V2G with dynamic containment are shown in Table 14. The payback periods of V2G with an lower hardware cost £1000 are also presented in Table 14. The payback years results did not take the impact of into consideration targeted charging review, which was launched by Ofgem to tackle the unfair outcomes for consumers caused by the inefficient utilisation of the network [135]). It is noteworthy that not all 320 chargers joined the frequency response trials at the same time as the plug-in availability was around 70% for most parts of the project.

TABLE 14. Simulated Annual Revenue From V2G Using Tariff Optimisation and Related Ancillary services [136]

Scenario	Ancillary service price	Revenue	Simple Payback Years
V2G	-	£340	5
V2G + FFR	£3.3-9/MW/h	£513	3
V2G + DC	£17/MW/h	£725	2

E-Flex connected 100 EVs to a V2G system and also investigated the responsibility of fleet managers to have a more environmentally friendly fleet by participating in V2G. 500 fleets with an average fleet size of 73 EVs were investigated. Consequently, 53% of fleet managers believe V2G can help fleet's transition into EVs and 54% of fleet managers believe the benefits from V2G can offset the inital investment of EVs [137].

EV-elocity, using eNovates charger, Nissan LEAF, Nissan e-NV200, and CHAdeMO connectors, focused on reducing CO2 intensity, reducing charging cost, and helping minimising battery ageing. In this project, calendar ageing and cycle ageing were tested separately and a combination model was built. Based on the degradation model, charging strategies were designed to mitigate degradation. As shown in the results, degradation can be mitigated by up to 26% in the first 100 days and battery life can be improved by 8.6% to

12.3% during a one-year operation using the designed strategies [138].

These first generation of demonstration projects discussed in this section have made great contributions in de-risking V2G technology. In the next phase of V2G applications, a mix group of EVs and charger protocols could be tested at the same time to mimic a real-world case scenario. In this case, the control of diverse technologies will be more complex as the delay profiles are different. Nevertheless, EV retailers are excellent locations for such demonstration projects as mix of chargers and vehicles are located in one location.

VIII. SOCIETAL IMPACTS

Previous sections summarized the economic benefits of V2X technology for the grid, EV owners, and other market players. In addition, bidirectional charging hubs have multifaceted societal benefits that positively impact all parts of society, including deprived regions. V2X is a promising technology to support better management of electrical power grids, which, in turn, has profound societal benefits as it enables higher levels of integration of renewable sources, reduces reliance on carbon-intensive fuels, and helps mitigate climate change. Lower energy costs, achieved through efficient grid management and renewable integration, ease the financial burden on low-income households and small businesses, freeing up resources for other essential needs. These benefits are discussed in this section.

A. WIDER SOCIETY

The primary environmental benefit of the V2G system is further decarbonization. A study in [139] demonstrated that integrating the V2G system within a greener energy system can reduce carbon emissions by up to 25%, thus slowing global warming, mitigating air pollution, and reducing related illnesses.

The V2G system achieves decarbonization in multiple ways. By utilizing EVs for frequency response regulation and reserve services instead of conventional generators, the V2G system offers an environmentally friendly alternative in the ancillary services market. Additionally, the maturing of controlled charging has been shown to decrease oil usage and carbon emissions through load shifting [140]. Moreover, the V2G system will significantly accelerate the further rollout of transport electrification, indirectly contributing to decarbonization.

Past studies have also found that increasing EV fleet penetration, empowered by the V2G system, can reduce regional on-road pollutants (including ozone), thus addressing regional inequalities in air quality [141]. However, as explained in [142], the major contribution to decarbonization comes not primarily from the ancillary market or controlled charging, but from the integration of renewable energy. The idle electricity stored in EVs can serve as an invisible pillar to support the system during wind lulls or solar power shortages, making the wholesale energy market "greener".

Secondly, the V2G system can potentially reduce social inequity by improving energy affordability and charging infrastructure availability. By participating in grid services, low-income families can reduce their energy costs [119]. [143] pointed out that social equity is significantly sensitive to factors such as charging infrastructure location and charging cost. Thirdly, consumers benefit by participating in ancillary services. Due to EV's high efficiency and fast response, the biggest economic value will come from frequency services. availability to provide V2G (in hour).

Besides, customers can also gain revenues by engaging in smart charging (off-peak charging) and bi-directional charging (V2G and V2H). Compared to large-scale wind resources, local solar energy is connected closer to consumers (easier to obtain and store), which explains why the benefits of V2G were discussed more about solar energy in [144]. Optimized charging time with the complement of self-consumption from PV energy entails a reduced electricity bill, although the revenue is highly dependent on photovoltaic systems' dimensions and household size [145]. Charging the vehicle during off-peak time and using the available and more affordable electricity stored in the vehicle when it is necessary can also save the household's electricity cost. Therefore, the economic benefits to consumers are tempting. Sciurus Trial, a project that was carried out across the U.K. in 2020, indicated an annual benefit of £340 from V2G using managed chargers, which increased to £725 if including the participation in ancillary service (Dynamic Containment) [146].

B. IMPROVING SOCIAL EQUITY

Social equity is a critical consideration for the widespread adoption of any new technology. Demographic shifts in England and Wales, with 18% of the population identifying as non-white British and 24.4% over 60 years old by 2021 [147], underscore the importance of addressing social equity in technology development. V2X technologies, particularly bidirectional charging hubs, present an opportunity to create new revenue streams and promote EV ownership in underprivileged areas.

Low-income households, disproportionately burdened by transport and energy costs and more exposed to air pollution [148], stand to benefit significantly from EV adoption and V2G systems. However, charging infrastructure and policy development often favor areas with higher per capita incomes, where early adopters are more prevalent [149]. The affordability of home charging further exacerbates this disparity, leading to regional inequalities in EV charging access. Addressing this "chicken and egg" problem requires targeted investment in charging infrastructure in underserved areas, guided by public opinion and data-driven analysis of potential demand.

Affordability remains a barrier to widespread EV adoption, encompassing both the upfront cost of vehicles and charging costs. While the U.K.'s most popular EV models like the Tesla Model Y and MG4 are expensive, the nascent second-hand EV market lags behind the well-established used petrol car market, projected to reach 146.32 billion USD in 2023 [150]. Policy interventions to equalize home and public charging costs could stimulate public charging demand [151]. In the long run, the increasing penetration of renewable energy sources could drive down electricity prices, making EV charging more affordable for everyone.

C. BLACKOUT AND DISASTER RECOVERY

EVs, equipped with vehicle-to-everything (V2X) systems, offer a significant potential for disaster resilience and community support due to their inherent capabilities as mobile energy storage units. Natural disasters, while infrequent, can cause extensive damage to power grids, leaving communities without access to essential services for extended periods [152]. The increasing frequency and intensity of extreme weather events due to climate change further exacerbate the vulnerability of power grids, pushing components beyond their operational limits [153].

EVs have already demonstrated their value in real-world disaster scenarios. For instance, during Winter Storm Elliott in the southeastern United States, EV owners utilized vehicle-to-load (V2L) and vehicle-to-home (V2H) functionalities to provide power during outages [154]. Similarly, following earthquakes, EVs have powered critical infrastructure like community centers and provided electricity for first responders' tools and command centers [155]. Research into home energy management systems, such as the algorithm proposed in [156], further highlights the potential for EVs to enhance grid resilience during and after disasters by prioritizing essential appliance usage.

The utilization of EVs as mobile energy resources not only offers practical solutions for power restoration but also contributes to a more resilient and sustainable energy system. By integrating EVs into disaster preparedness and response strategies, communities can leverage this technology to mitigate the impact of outages and accelerate recovery efforts.

IX. CONCLUDING REMARKS

A. OPEN RESEARCH AREAS

This comprehensive review of V2X technology and bidirectional charging hubs underscores several avenues for further research and development:

1) *Broadening the Diversity of EV Models in V2G Studies:* The current overrepresentation of Nissan vehicles in V2G studies limits the generalizability of findings and the development of comprehensive integration strategies. To address this, future research should actively engage a wider array of EV models, incorporating diverse battery chemistries, capacities, and charging profiles. This will facilitate a more nuanced understanding of the challenges and opportunities associated with V2G integration across the EV spectrum, ultimately contributing to more effective and scalable solutions.
2) *Investigating Socioeconomic and Behavioral Factors:* The successful integration of bidirectional charging hubs into motor retail settings requires a holistic understanding of not only the technical and economic aspects but also the socioeconomic and behavioral factors that influence consumer adoption. Future research should explore consumer perceptions, attitudes, and preferences regarding bidirectional charging, as well as the potential barriers and incentives that could influence their participation. This will enable the development of targeted strategies to promote the widespread adoption and utilization of bidirectional charging infrastructure.
3) *Enhancing Grid Integration and Resilience:* While current research primarily focuses on maximizing grid-to-vehicle charging, the potential of bidirectional charging hubs to enhance grid integration and resilience remains largely untapped. Future research should investigate the optimal placement of hubs in relation to not only grid supply points (GSPs) but also critical infrastructure, renewable energy generation facilities, and areas with high EV adoption rates. This will enable the development of strategies to leverage bidirectional charging for ancillary services, demand response programs, and peak shaving, ultimately enhancing grid stability and reliability.
4) *Optimising onboard Charger Performance:* In V2X applications, onboard charger performance is often a bottleneck. Communication delays when initiating charging and reaching full power do not meet the minimum time required to respond to ancillary market signals. Additionally, data from six EV models reveal a lack of standardization in charger communication delay profiles. To achieve mainstream adoption of V2G (Vehicle-to-Grid) technology, it is crucial to carefully evaluate the trade-off between optimizing onboard chargers and the potential gains from V2G markets.
5) *Developing Holistic Simulation Environments for V2G Systems:* The development of advanced co-simulation platforms that integrate communication and power flow simulations is crucial for accurately modeling the complex and dynamic interactions within V2G systems. These platforms will enable a more comprehensive understanding of V2G system behavior, facilitating the development of robust control strategies, optimal dispatch algorithms, and effective demand response mechanisms to ensure the reliable and efficient operation of V2G systems.

B. CONCLUSION

In this paper, we have presented a comprehensive literature review on the challenges and opportunities for EV retailers as bidirectional charging hubs. We classified relevant literature into sections addressing EV battery technology, associated degradation mechanisms for G2V and V2X applications, and an analysis of bidirectional chargers and associated industry protocols. We also examined ancillary services in the U.K., focusing on performance requirements for specific energy markets. By utilizing publicly available onboard charger datasets for six different EV models, we assessed the suitability of various EV fleets for each market type. Finally, we analyzed recently launched V2G projects and the potential impacts of bidirectional charging hubs on the broader society.

From this review, we identified the following challenges to transform EV retailers into bi-directional charging hubs:

1) *Infrastructure Limitations:* The power rating of bidirectional chargers is often limited to 10 kW, hindering the provision of ultra-rapid charging services. Further development of bidirectional charger technology is needed to support both G2V and V2G services effectively.
2) *Business Model Innovation:* Unlike conventional public charging hubs or domestic V2G applications, EV retailers own and use EV batteries intended for sale. The balance between battery degradation costs and financial gains from V2G services requires careful consideration. New business models are needed to ensure customer trust and transparency regarding battery health. Standardized, internationally accepted battery SoH measurement techniques are crucial to support a thriving second-hand EV market.
3) *Battery Degradation Management:* EV retailers must develop strategies to mitigate the effects of calendar ageing on EVs stored at their sites, particularly in cold weather. This may involve passive or active battery heating and maintaining optimal SoC levels.

Similarly, key opportunities for EV retailers include:

1) *Leveraging Existing Physical Space:* EV retailers already possess suitable locations for charging hubs, eliminating the need to acquire and finance new real estate.
2) *Aggregated Capacity for Ancillary Services:* The aggregated capacity of EV fleets at dealerships can meet the minimum volume requirements for participation in ancillary service markets, creating additional revenue streams and potentially reducing EV ownership costs.
3) *Existing Network Connections:* Many EV retailers already have established network connections, facilitating the installation of EV chargers without delays due to limitations imposed by distribution system operators.

This literature review highlights the potential for EV retailers to become significant players in the EV charging business and ancillary service markets. However, further research is needed to equip EV retailers, who traditionally operate outside the power grid domain, with the necessary knowledge and tools to successfully navigate this evolving landscape.

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