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RESEARCH ARTICLE

Reaping the Benefits of Smart Electric Vehicle Charging and Vehicle-to-Grid Technologies: Regulatory, Policy and Technical Aspects

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ABSTRACT Electric vehicles (EVs) are penetrating rapidly into the transport sector while making profound impact on the electricity and energy sectors. Although EVs have many benefits, it poses several challenges to power grid operators. Uncoordinated EV charging is one of the critical issues that need to be addressed to mitigate the potential adverse effects on power grids. Smart charging and vehicle-to-grid (V2G) technologies enable smart power transfer between the EV and the grid considering network conditions and requirements. Therefore, smart charging and V2G can alleviate the adverse effects but requires policies and regulatory frameworks to increase the uptake of these technologies. This paper presents a critical review on the effects of unmanaged charging of EVs, and the benefits of smart charging and V2G considering the published research studies and real-world field trials. Simulation case studies also demonstrate the adverse effects of uncoordinated charging and the benefits of smart charging. According to this study, unmanaged charging increases the peak load, which in turn causes high power losses, voltage violations, voltage unbalance, reduction of transformer lifespan and harmonic distortion. This study has established that smart charging alleviates these network issues and brings a wide range of economic, social, and environmental benefits. In particular, role of smart charging as a mandatory requirement for attaining the net-zero decarbonization target of the transport sector is highlighted. Finally, the paper sheds light on the policy, standards and regulatory frameworks that need to be implemented to promote smart charging and V2G technologies among EV owners and charging infrastructure developers.

INDEX TERMS Electric vehicle (EV), renewable energy, smart charging, uncoordinated charging, voltage violations, voltage unbalance and vehicle to grid (V2G).

I. INTRODUCTION

Electric vehicles (EVs) are rapidly superseding the fossil-fuel based vehicles due to the advancements in EV technology (e.g. range, speed and charging capabilities), incentives given by governments and policy directives to reduce greenhouse gas emissions in the transportation sector [1]. During the last decade (2010 – 2019), over 7 million EVs (e.g. electric cars, buses, vans and heavy trucks) were added to roads around the world, indicating an average annual growth rate of 30% [2]. Currently, nine countries have more than 100,000 electric vehicles on their roads, and more than 20 countries have reached a market share above 1% [2]. According to the IEA's Global Electric Vehicle Outlook, the number of EVs on roads is expected to reach 145 million by 2030 [3]. If governments ramp up their efforts to meet international energy and climate goals (e.g. United Kingdom has committed to a net-zero emissions target by 2050; Germany has planned to achieve greenhouse gas neutrality by 2045), the global EV fleet could increase further, and will reach 230 million by the end of the decade [3]. These astounding EV forecasts indicate the level of forethought required in grid planning and operation to alleviate any potential impacts on the power grid.

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According to some policy scenarios, by 2030 global electricity demand from electric vehicles can reach 550 TWh, which is a six-fold increase from the 2019 energy demand [4]. The share of demand due to electric vehicles in total electricity consumption has grown by 4% in Europe [2]. Under the sustainable development scenario (i.e., an integrated approach to achieve internationally agreed objectives on climate change, air-quality and universal access to modern energy), the electricity demand will increase by nearly eleven-fold relative to the 2019 level, to almost 1,000 TWh, the EV share of total demand is ranging from 2% in Japan to 6% in Europe [3]. The National Grid, UK has estimated that the electricity demand in the transportation sector will reach 153 TWh by 2050, which is a significant increase compared with the 2020 level (1 TWh) [5]. According to the Australian Energy Market Operator (AEMO), if all Australia's 19 million vehicles [6] were electrified, that would increase the Australia's electricity consumption by one third [6], [7]. This enormous challenge should be managed effectively by using the opportunities exploited from EVs. For example, these EVs have approximately the same energy storage capacity as five Snowy 2.0 pumped hydro power schemes [8], and hence if the EV fleets are managed effectively, that can avoid future investment on storage systems.

Fast-charging infrastructure is gradually being deployed to respond to the growth in relative share of EVs with higher battery capacity and power requirements. When an EV is connected to a charger, it would either start charging the EV battery immediately or start charging after a time delay. If the charging time of the majority of EVs coincides with each other, it would result in a large power/ energy demand on the power grid, and result in unacceptable low voltage in the distribution network. Such a situation is commonly referred to as '*uncoordinated charging,*' or '*unmanaged charging.*' A random or unmanaged EV charging could adversely affect the distribution grid, such as an increase of real power losses, violation of voltage limits, and overloading of distribution network assets, such as distribution transformers and cables/lines [9]. Moreover, uncoordinated EV charging will also increase the operation cost. Since it increases the peak demand and will require expensive fast-start generation units to cater for that additional demand, such as gas-turbine generators [9]. Similar consequences could be anticipated from the unmanaged vehicle-to-grid (V2G) schemes.

Smart-control charging enables control of the charging process in an organised way, it is often seen as an important step towards a successful grid integration of EVs, and a profitable operating model for public EV charging stations [10]. Coordinated smart charging can improve the operational performance of the power grid and can minimise the charging cost by adopting dynamic pricing policies [11]. Smart charging can pass the benefits to the individual users directly by reducing their charging costs and indirectly by minimizing distribution system losses, reducing distribution network investment costs, minimizing loss of life of transformers, peak shaving and valley filling [10].

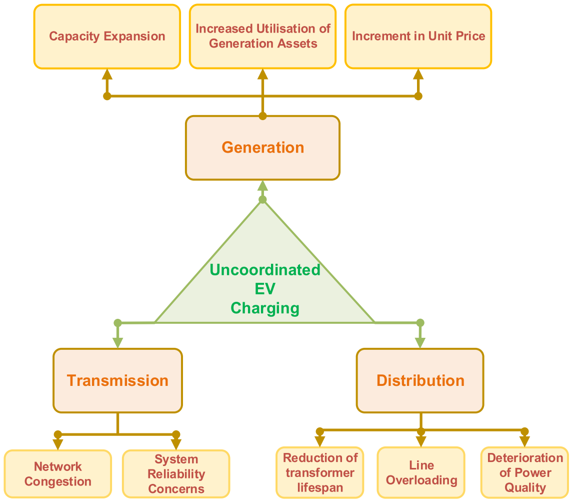

FIGURE 1. **Effects of uncoordinated EV charging.**

The International Renewable Energy Agency (IREA) believes smart charging and user incentives are the two key factors for unlocking the flexibility potential of EVs, which is required for successful grid integration of EVs and renewable energy in the future [4]. Therefore, smart charging could play a pivotal role in mitigating the adverse effects on power grids due to uncoordinated EV charging.

Although the technical aspects of smart charging are well investigated, to apply the smart charging schemes effectively, it is essential to implement strategic policy directives to support the smart charging schemes. This paper will review the issues arising from uncoordinated EV charging and V2G, and then demonstrates the technical issues arising from uncoordinated EV charging in distribution networks using a case study. Moreover, this paper reviews the benefits of smart charging demonstrated through field trials and research studies, and further demonstrates the benefits of smart charging via quasi-dynamic simulations. Finally, this paper makes policy and regulatory recommendations, and stipulates requirements for standards to successfully implement the smart charging and the V2G schemes in power grids.

II. OPERATIONAL CHALLENGES OF UNCOORDINATED EV CHARGING

Uncoordinated EV charging would result in numerous challenges to power system operators, and these challenges become more severe as EV penetration increases. This section critically reviews major operational challenges that power grid operators may face with EVs, such as grid congestion, peak demand increase, power quality issues, power losses, and generation adequacy requirements. Finally, it demonstrates some challenges via a simulation case study based on a typical low-voltage (LV) network. The impact of EVs on the power grid can be analyzed considering several factors, such as EV penetration levels, charging strategies, EV battery characteristics, location of charging, charging patterns, charging time, state-of-charge (SoC) of the battery, EV fleet charging patterns, driving patterns of EVs, driving distances, tariff schemes, and demand response techniques [1]. Effects of uncoordinated EV charging on generation, transmission and distribution are illustrated in Fig. 1.

A. IMPACT ON GRID CONGESTION AND NETWORK PEAK DEMAND

Uncoordinated EV charging significantly influences the power distribution grid. EVs require a large amount of electrical power/ energy for the charging process (e.g., 1.4 – 25 kW for Level 1 to 3 charging). This charging demand can lead to very high undesirable peaks in the electricity consumption. Qian et al. have shown that if domestic charging is uncoordinated, 10% penetration of EVs can cause a 17.9% peak demand increase, and 20% EV penetration would increase the peak demand by 35.8% [12]. Wang et al. have also shown that if 30% of total load were EVs, then uncoordinated charging would increase the peak demand by 53% [13].

The ''My Electric Avenue'' project in the UK investigated the impact of EV charging clusters on network congestion and has shown that peak demand could be doubled up with uncoordinated EV charging [14]. This study also demonstrated that, even with small capacity chargers (e.g., 1.4 kW to 7.4 kW), network congestion occurs at around 50% EV penetration on a local network. It has been predicted that, if EV charging is unmanaged, 32% of low voltage (LV) feeders across Britain would require reinforcements by 2050. Transformer overloading will also be aggravated by EV charging. For example, ''My Electric Avenue'' project has shown that uncoordinated charging can lead to 32% of distribution transformer replacement in the UK when 40-70% of customers have an EV [14].

A trial by Xcel Energy in Colorado concluded that at EV market penetration of 5%, up to 4% of distribution transformers could be overloaded if all-electric vehicles are charged at the peak time [15]. The EV modelling study done in New England, United States has shown that if 25% EVs connected to the grid are charged in an uncoordinated manner, it would increase the peak demand by 19%, and hence requires a significant investment to improve generation capacity of the grid [16]. However, spreading the load over the evening hours could reduce the peak demand increase between 0% to 6% [17]. EV charging during the off-peak hours could avoid any increase during the peak demand period [16]. A study conducted in California (USA) with 23% EV penetration have found that it could increase the peak load by 11.14% with uncoordinated charging mode [16]. McKinsey study on EV integration in Germany found that when the local EV penetration reaches 25%, peak load can grow by 30% under uncoordinated charging [18]. Another study assessed the impact of introducing 2.5 million EVs in Turkey (represents 10% of total vehicles in Turkey), and it has concluded that it would increase the peak load by 12.5% with uncoordinated charging [2]. These studies have confirmed the adverse effects of uncoordinated EV charging, mainly on the power grid congestion and the peak demand. Therefore, these network congestion issues can be mitigated by appropriately managing the EV charging [14].

B. IMPACT ON POWER QUALITY

Several power quality challenges are emerging with uncoordinated EV charging. Power quality is assessed considering several factors, such as voltage violations, voltage unbalance, short- and long-term voltage sags and swells, poor power factor, harmonics, and flicker. Random uncoordinated EV charging can affect any of the above factors, and hence result in poor power quality [19], [20]. Poor power quality can reduce the lifespan of equipment (e.g. distribution transformers) and reduce grid reliability.

The Electric Power Research Institute (EPRI), California, has demonstrated how uncoordinated charging of EVs can cause the feeder voltage profile to violate its stipulated limits imposed by grid-code standards by conducting a trial in a LV network of South Dublin, Ireland [14]. Dubey et al. have investigated the impact of EV load clustering on distribution networks under different EV penetration levels and charging methods, and have demonstrated the effects on peak load demand and distribution voltage variations [21].

Masoum et al. have investigated the effects of EV charging on voltage deviations and have shown that the node voltage has fallen below the regulatory limit for all uncoordinated charging scenarios [22]. According to a power quality study the voltage total harmonic distortion (THD) level has increased to 11.4% due to rapid and random EV charging, which has violated the 8% VTHD limit stipulated by EN 50160 standard [1]. Deilami et al. have also observed that VTHD levels could increase to 45% when 18 EVs are randomly charged during the peak hours [23]. The harmonic emission study conducted using EV chargers from the Portland State University have unraveled the fact that the current total harmonic distortion (ITHD) could reach levels high as 12 - 24% with the DC fast charging, while the VTHD was limited to 8% [24]. A Dutch field study demonstrated that uncoordinated charging might lead to local blackouts and significant phase unbalance in the low-voltage grid [25].

C. INFLUENCE ON POWER LOSSES

EV charging infrastructure, such as charge-discharge cycles of batteries contribute to energy losses. From the distribution system operator's point of view, the power loss during charging is an economic concern and should be minimized, and hence transformer and feeder overloads can be minimized up to some extent. With 60% EV penetration level and different charging strategies, Fernandez et al., observed up to 15% increment in the investment cost of distribution network, and 40% increment in energy losses during the off-peak hours [26].

Pillai and Bak-Jensen investigated the charging impact of EVs for Danish distribution network. The result of the study revealed that at 50% EV penetration level, the uncoordinated charging scenario has increased the system losses by 40% [27]. Deilami et al. investigated the impact of EV charging on power losses and have shown that power losses have increased for all the uncoordinated charging cases [28]. Habib et al. found that random charging scenarios with level 2 charging condition and significant EV penetration can severely impact the distribution network components, especially the power cables and power transformers, and thereby increase the losses of the system [1]. All these field trails and research studies have proved the adverse effects of uncoordinated EV charging on network power losses.

D. OTHER NETWORK EFFECTS

Large-scale EV deployment may not be possible due to generation adequacy issues, and therefore it is required to commission additional power generation resources to the grid or need to implement coordinated charging schemes [1]. If a charging infrastructure is not planned properly, the widespread adoption of EVs can significantly increase the substation load demand. Consequently, the capacity of the existing distribution grid may need to be expanded [21]. A study conducted in Barbados (with solar and wind generation supply of 64% of the load demand and considering more than 26,000 EVs by 2030) has demonstrated a five-times increase in generation costs with uncoordinated charging compared to the most efficient smart charging strategies [29]. Therefore, uncoordinated EV charging can also result in generation adequacy and economic issues. Thus, smart charging is required to avoid expensive grid reinforcement costs resulting from uncoordinated EV charging [2].

E. SIMULATION CASE STUDY: UNCOORDINATED EV CHARGING

A simulation case study was conducted using a feeder model shown in Figure 2. A 0.4 kV three-phase four-wire distribution feeder consists of 15 network access points (node T1 ~ T15), and at each node single household is connected to each phase. At the upstream, feeder is connected to the 11 kV network via a transformer. A capacitor bank is installed at the end of the feeder (T15) to improve the voltage profile of customers connected to the end of the feeder. Simulations are conducted under different scenarios with the test network to illustrate the influence of EVs on the distribution network. This is a more realistic scenario, since most EV owners are charging vehicles at their homes [30].

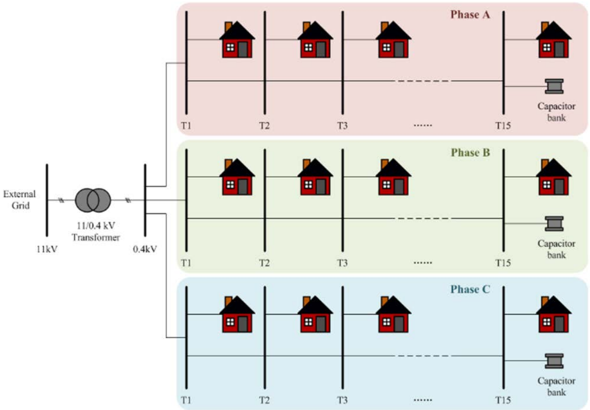

FIGURE 2. The test network model.

For base case scenarios, same load is considered for each customer. The following three base case scenarios are analyzed: (b1) 1.5 kW load for each customer, (b2) 3 kW load for each customer, and (b3) 3 kW load for customers on T1, T3, T5, T7, T9, T11, T13, T15, and 6 kW load for customers on T2, T4, T6, T8, T10, T12, T14.

1) EV CHARGING (G2V MODE)

Six EV charging scenarios are analyzed: (c1) A single EV charging at T1, (c2) A single EV charging at T8, (c3) A single EV charging at T15, (c4) three EVs charging at T1, T8 and T15, respectively, (c5) four EVs charging at T2, T6, T10 and T14, respectively, (c6) five EVs charging at T2, T5, T8, T11 and T14, respectively. The load of each customer is set at 3 kW and the charging power of each EV is assumed to be 7.2 kW.

The voltage at each terminal is presented in Fig. 3. Each row represents a simulation scenario. The base cases are represented in top three rows (i.e., (b1) ~ (b3)). According to base case scenarios, it is obvious that the voltage decreases along the feeder. When the load is 1.5 kW, the voltage drop is 4.5% of the nominal voltage; when the load is 3 kW, the voltage drop is 7.7% of the nominal voltage; when the loads are 3 kW and 6 kW, the voltage drop is 13.9% of the nominal voltage. Thus, with the increase of the load, the voltage drop increases. According to the comparison cases (c4)~(c6), the voltage decreases further with more EVs are charging in the LV feeder. The voltage drop is up to 22.3% of the nominal voltage when there are 5 EVs charging in the feeder. Moreover, comparison cases, i.e. scenario (c1)~(c3), show that EVs charging downstream of the feeder result in lower voltage than the EV charging upstream of the feeder.

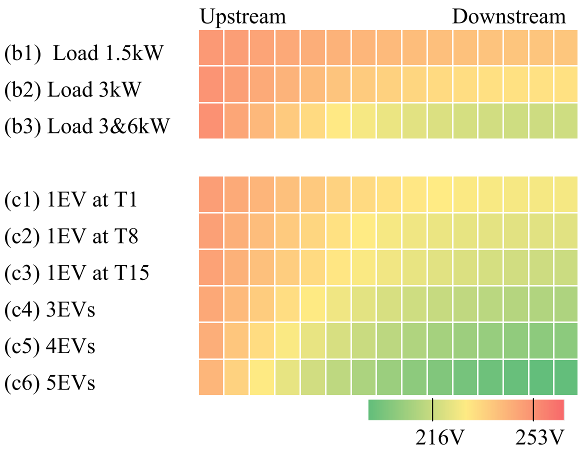

FIGURE 3. The voltage performance of each terminal under EV charging (G2V).

The voltages of downstream terminals with 3 EVs, 4 EVs and 5 EVs are lower than 216 V (94% of the nominal voltage).

The loading of each distribution line is presented in Fig. 4. Base case scenarios (i.e., b1 ∼ b3) have shown a higher loading in distribution lines under high power load (i.e. 6 kW) at each customer. The maximum line loading observed was 130% (at the upstream in the base case (b3)). Moreover, the loading decreases along the feeder. In comparison cases, EVs located downstream of the feeder result in higher loading (maximum loading is 87.9% in comparison case (c3)) comparing with EV located upstream of the feeder (maximum loading is 69.9% in comparison case (c1)). In scenarios with 3 EVs, 4 EVs and 5 EVs, the lines are overloaded at the upstream of the feeder with maximum loading values of 106%, 138% and 164%, respectively.

Network unbalance is also analyzed considering the unbalanced connection of EVs between three phases: A single EV is connected in phase A at T8; 3 EVs are connected in phase B at T1, T8, T15; 5 EVs are connected in phase C at T2, T5, T8, T11, T14. Terminal voltages along the feeder are presented in Fig. 5. The voltage unbalance factor (VUF) of each terminal is presented in Table 1. It shows that the voltage unbalance is more severe at the feeder's downstream (4.9%) than at the upstream (1.6%). The line loading of each phase along the feeder is presented in Fig. 6, which reflects that overloading issue exists in phase C (maximum loading 206%).

2) EV DISCHARGING (V2G MODE)

Apart from the G2V mode presented above with EVs charging from the grid, EVs can also operate in V2G mode by discharging power to the grid. Same base case scenarios are considered here; (e.g. (b1)∼(b3)). In addition, seven scenarios with EV discharging (V2G) to the network are analyzed: (c1) A single EV discharging at T1, (c2) A single EV discharging at T8, (c3) A single EV discharging at T15, (c4) three EVs discharging at T1, T8 and T15, respectively, (c5) six EVs discharging at T2, T4, T6, T10, T12 and T14, respectively, (c6) nine EVs discharging at T1, T3, T5, T7, T8, T9, T11, T13 and T15, (c7) twelve EVs discharging at all terminals except T4, T8 and T12. In comparison cases, the load of each customer is 3 kW. The discharging power of each EV is 7.2 kW.

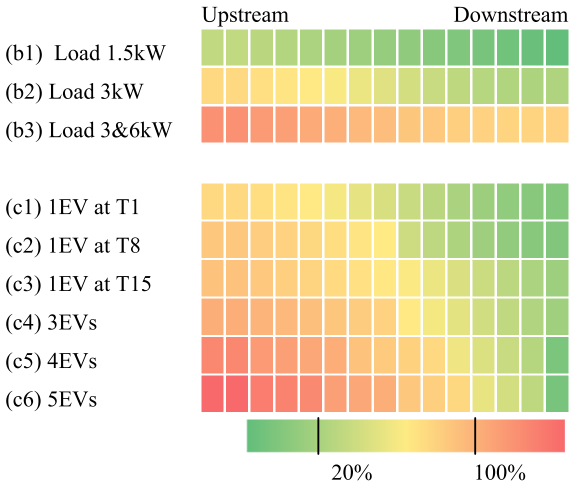

FIGURE 4. Line loading of each distribution line under EV charging (G2V).

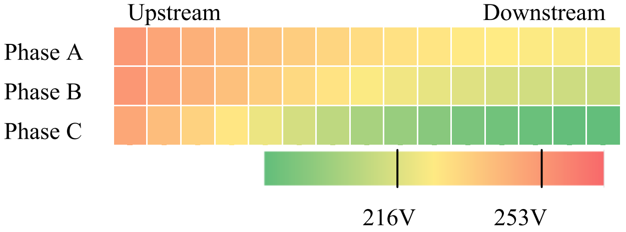

FIGURE 5. Voltage of each phase under unbalance EV penetration.

The terminal voltage and line loading between terminals are presented in Fig. 7 and Fig. 8 respectively. It can be observed that when the number of V2G EVs is low (less than 6), the EV discharging power is less than the load. Hence the distribution network imports power from the grid, and the terminal voltage decreases along the feeder. When the number of EVs is high (more than 6), then the EV discharging power is more than the load. The distribution network exports power to the grid, and the terminal voltage increases along the feeder. Overvoltage may occur at downstream of the feeder. The voltage at T15 in cases (c6) and case (c7) are 110% and 113% of the nominal voltage. Moreover, it is obvious from the colour map in Fig. 8 that the EV discharging reduces the line loading. When 6 EVs are discharging in the network, the line loading reaches the minimum value (the upstream line loading is 20.4% in case (c5)).

The simulation scenarios clearly demonstrate the issues of uncoordinated EV charging and discharging in power grids. Therefore, with the increasing EV penetration, it is essential to implement smart charging and V2G strategies for EVs to avoid these issues in power distribution networks.

III. SMART COORDINATED EV CHARGING AND V2G

Smart charging enables EVs to charge during most optimal time periods of the day (e.g. low demand periods with least

TABLE 1. The VUF of each terminal.

Terminals	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
VUF (%)	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.2	4.5	4.7	4.8	4.9	4.9

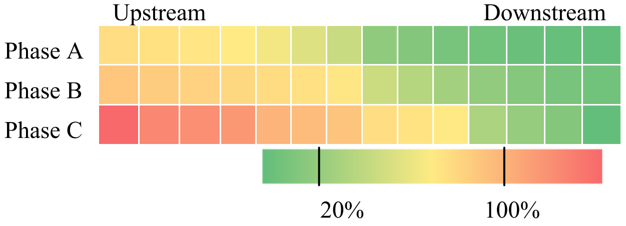

FIGURE 6. Line loading of each phase under unbalance EV. penetration.

energy cost) while delivering benefits to both the EV owners and the power utilities. Additional infrastructure is required for smart charging, such as smart charging enabled chargers, a communication layer and a processing infrastructure. A schematic diagram of the smart charging scheme is shown in Fig. 9.

As illustrated in Fig. 9, the smart charging operator collects the data from the EV (via the car manufacture's original equipment manufacturer (OEM) cloud), EV owners and network operators (e.g., transmission system operator (TSO), distribution system operator (DSO)), and then executes optimisation algorithms to devise smart charging commands (e.g. start and stop times for charging, charging rate) for EVs. A similar infrastructure could be used for smart V2G schemes. Smart charging algorithms typically consider the network conditions (e.g. peak demand, voltage profile, power quality indices), and optimize charging cost, carbon emissions, and EV owner preferences.

Several studies have proved that effective EV charging management strategies are capable of supporting high EV penetration levels in distribution networks [31]. Smart charging could be considered as a flexible resource for power grid operators to reshape their generation portfolio. Therefore, it is the most recommended charging method for mitigating network issues caused by unmanaged EV charging. To implement smart charging, smart metering and communication systems must be implemented to control and coordinate the EVs individually, while communicating with the DSO and the TSO. Subsequently, smart charging allows attaining the highest EV penetration level without violating the network technical limits [22].

Smart charging can optimize the electricity demand to avoid network constraints, such as network congestion. Similarly, smart V2G can optimize time and power demand [32], and reduce the daily electricity costs, voltage deviations, assist in flattening the voltage profile of distribution feeders, reduce line currents, and large load variations at distribution transformers [33]. Smart charging of EVs enables peak shaving and provision of ancillary services [14]. Moreover, incremental investments and high energy losses could be avoided with smart charging, and also renewable energy curtailment and network congestion could also be prevented with smart charging [32]. Slow charging is best suited for the "smart charging" approach, since it boosts system flexibility [34]. Furthermore, smart charging aids to maintain grid stability by balancing the electricity generation with the load demand, for example, EVs can provide power when there is a lack of renewable energy supply in the network, and they can charge when there is an excessive renewable energy supply in the power grid [35].

As discussed in Section 2, uncoordinated EV charging could greatly affect the network capacity by increasing the peak demand, and hence increase network congestion significantly. There are several methods proposed in the literature to manage the grid congestion, such as demand management, generator rescheduling, modifying the network topology, or installation of conventional compensation devices, such as flexible AC transmission system devices. However,

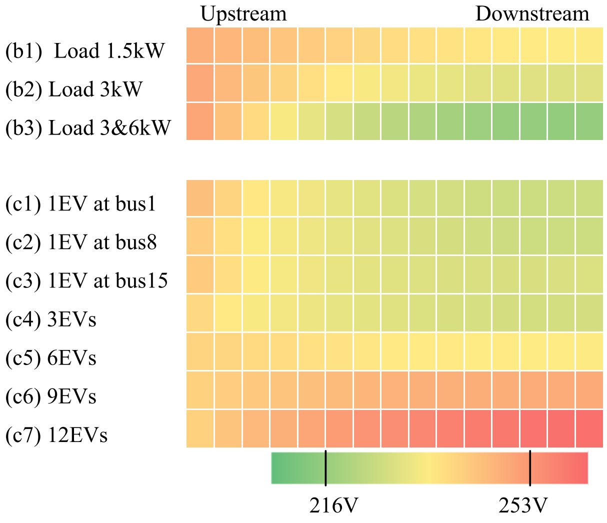

FIGURE 7. The voltage performance of each terminal under V2G.

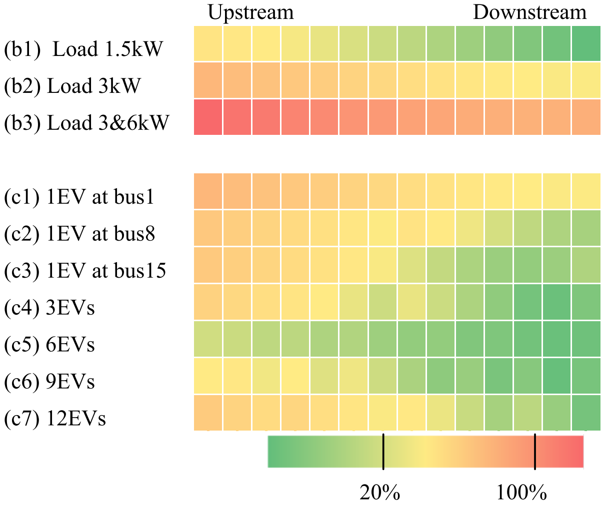

FIGURE 8. Line loading of each distribution line under V2G.

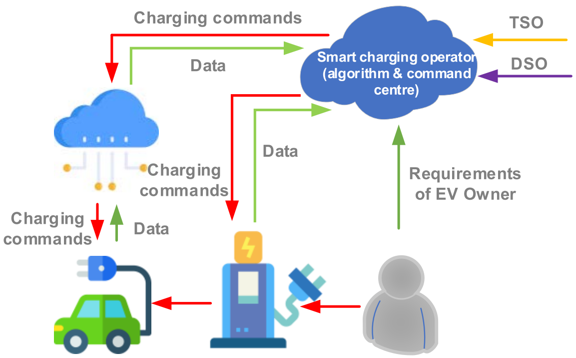

FIGURE 9. A schematic of the smart charging infrastructure.

TABLE 2. Smart charging and V2G trials.

S.no	Trial name	Description/ Learnings from the project	Country
1	ENP (Electric Nation Project) [42]	This is the largest smart charging trial project in the world to date. Project had 673 participants and recorded over 130,000 charging events in a 2-year trial period. The study has shown that demand management is technically feasible and acceptable to most participants. Data from smart chargers can be used as a reliable data source for future planning activities. Study data has shown that there is a lot of flexibility in EV charging. Therefore, informing and empowering EV drivers is essential for promoting smart charging. Trial data also shows that time of use incentives are highly effective to move demand away from the evening peak, and hence optimal incentive should be used to achieve the best outcome.	UK
2	European INVADE Horizon 2020 Project [43]	This is the largest smart charging trial, which mainly focuses on the capability of renewable energy to fulfil the local EV charging demand. The trial was based on the charging rate (never allowed charging below 14 A). SoC was not considered as a parameter.	Netherlands [44]
3	Origin Energy Electric Vehicles Smart Charging Trial [45]	The primary objectives of this project are understanding the benefits of smart charging and barriers to smart charging, including improving the understanding of EV driver behaviour, and willingness to accept third party control. Also, trial evaluates the incentives required to encourage future participation in charge management programs.	Australia
4	CHARGE [46]	Refueling tomorrow's electrified transport is to create an overarching map of where EV charging points will be required and where they can be best accommodated in the electricity grid.	UK
5	Parker (Danish project) [47]	This project has shown that V2G has the potential to play a significant role in providing grid flexibility and has the potential to gauge extra revenue from EVs. Also highlighted some challenges, including uncertainty about the degradation of batteries, lack of standardization of communication protocols and lack of consumer knowledge of the V2G system.	Denmark

these methods come with an extra cost, on the contrary, smart charging with an optimal EV charging schedule (EVCS) can allocate the charging load to prevent power peaks [11]. Therefore, EVCS plays a significant role in mitigating the adverse effects of large EV charging demand without having to upgrade the power network capacity [10]. Lopes et al. also concluded that large-scale EV adoption is possible without major grid reinforcement with advanced centralized control strategies, such as smart charging [36]. Moreover, smart charging can improve power quality by effectively controlling voltage and power factor [21].

By shifting the charging load over the time and controlling the rate of charging, two approaches have been proposed considering a residential area with 63 households; one strategy was based on classical quadratic programming (QP), and the other strategy was based on market based multi-agent system (MAS) coordination [37]. Results have demonstrated that controlled charging assists to reduce the peak load, load variability, and deviations from the nominal grid voltage [37]. Energy-packet based (EPB) scheduling and uncoordinated charging strategy with two charging modes are compared by Graber et al. to investigate the impact of deep penetration of EVs in distribution networks by using University of Salerno (UniSA) microgrid model. The results have confirmed the capability of the EPB strategy to flattening the demand profile while fulfilling the EV charging needs [38].

Smart charging of EVs allows customers and network operators to plan EV charging profiles to obtain technical and economic benefits [39]. Dubey et al. investigated and proposed two strategies considering both utility and customer benefits as objectives, and they have significantly decreased the substation load demand by optimally shifting the EV load demand to off-peak hours [21]. In the first strategy, utilities indirectly control the EV charging using time-of-use (TOU) pricing, and hence it has significantly decreased the peak load demand, and has mitigated the transformer overloading and heating concerns [21]. In the second strategy, utilities directly control the EV charging rates and the start time of EV charging using smart charging algorithms to decrease the total electricity cost in a real-time electricity market. Although this scheme is designed to mitigate voltage variability issues at the secondary customer location, the algorithm is successfully able to deliver utility benefits by minimizing the substation peak load demand. The proposed method significantly decreases the impacts of EV load charging on system peak load demand and feeder voltages [21].

A. SMART CHARGING BENEFITS DEMONSTRATED THROUGH FIELD TRIALS

Several real-world cases studies and trials have also demonstrated the benefits of smart charging. Real-world EV trials such as "My Electric Avenue" project demonstrated that smart charging could avoid network reinforcement cost [14]. Smart V2G can avoid local network congestion caused by demand peaks and defer network investments [14]. A recent study by EVENERGI on the South Australian electricity network has found that "If EVs are managed correctly, they have the potential to improve network asset utilization" [40]. According to McKinsey, the smart charging can reduce the peak load to 16% from 30% under 25% EV penetration in the grid [16]. Turkey's 10% EV penetration case study has revealed a 28% reduction (12.5% to 3.5%) in peak load by utilising smart EV charging [2]. Under optimized charging mode, the peak load has reduced from 11.14% to 1.33% for 23% EV penetration scenario in California [15]. A study conducted by the French TSO (RTE) has also found that smart charging could alleviate the adverse impacts of uncoordinated EV charging, and it can be considered as a flexible resource for RES integration and decarbonization of the transport sector [41]. The smart charging and V2G trials are conducted worldwide, and their objectives and outcomes are summarised in Table 2.

B. BENEFITS OF V2G

Vehicle-to-grid (V2G) result in bidirectional power/energy flows between an electric vehicle's battery and the power grid. Three elements are required for successful V2G operation: 1) power connection to the grid, 2) control and communication between vehicles and the grid operator, and 3) on-board/off-board intelligent metering. Smart V2G appears to be the most beneficial and efficient strategy for both the grid operator and EV owners. Cooperation between the grid operator and vehicle owners or aggregators is important to realise the highest possible net return from the V2G schemes [34].

V2G can improve the performance of the electricity grid, such as efficiency, stability, and reliability [4]. The electric vehicles are usually accumulated and treated as dynamic distributed energy sources in the V2G schemes to support the electric grid by providing ancillary services [48]. A V2G-capable vehicle can offer reactive power support, active power regulation, optimal utilization of variable renewable energy sources, load balancing, current harmonic filtering and can enable ancillary services, such as voltage and frequency control, and provision of spinning reserve [34]. The V2G technology with suitable control can offer inertia support and system strength [49]. This would allow the system operators to operate the power system securely with less synchronous generation.

Nevertheless, V2G needs to overcome several challenges, such as premature battery degradation, investment on communication infrastructure to facilitate the communication between the EV and the grid, effects on grid equipment, other infrastructure changes, social, political, cultural, and technical obstacles [50]. Although V2G operation may reduce the lifespan of EV batteries, it is expected to offer economic benefits for EV owners and grid operators [51].

C. ECONOMIC, SOCIAL AND ENVIRONMENTAL BENEFITS OF SMART CHARGING

Along with the other benefits offered to power grids, smart charging can also maximize the utilization of available green energy sources, minimize energy losses, maximize the grid load factor, and maximize fully charged EVs. Furthermore, smart charging assists to achieve financial objectives, such as minimizing of generation cost, minimizing of running cost, benefits maximization for aggregators, and also helps to achieve socio-environmental objectives such as reduction of CO_2 and greenhouse gas (GHG) emissions [2], [33], [35].

EV charge and discharge management could defer or entirely avoid investment in transmission and distribution network assets, such as power lines and transformers [1]. Also, it can reduce network costs for all connected customers [52]. In concise, a significant reduction can be realized in terms of both investment and operation costs, if the EV users adopt a smart charger instead of an uncoordinated charger [1].

Smart V2G can assist in increasing renewable power penetration by using that energy for EV charging, thereby reducing the peak demand by discharging that energy during peak periods [53]. Smart charging can also reduce charging cost [14]. Fernandez et al. have shown that it is possible to avoid up to 60–70% of the incremental investment with smart charging [26]. Ren et al. suggested a Bayesian network based real-time EV charging scheduling with the spot pricing of electricity, and has found that it can achieve 6% reduction in charging cost of EVs compared with the deterministic charging method. This was demonstrated considering uncertainties in the real-time EV charging scheduling with the actual parking data and PV generation outputs for an industrial zone [54].

A multi-objective optimisation methodology for EV fleet charging is proposed by Houbbadi et al. Study has used nonlinear programming considering all operating constraints, charging station constraints, power grid constraints to obtain an optimal charging power profile while minimizing the charging cost and battery aging cost. The results were compared with non-dominated sorted genetic algorithm (NSGA-II) results. The simulation study has shown that with multi objective pareto approach, both objectives can be satisfied and can achieve 20% reduction in annual electricity cost and 48% reduction in battery aging cost [9].

D. REVIEW OF SMART CHARGING ALGORITHMS

Charging algorithms that determine optimized charging schedules can reduce the negative effects of EV charging load on the distribution grid and optimize the consumption of renewable and intermittent energy sources [37]. Smart charging seeks active control of loads and can be programmed with deterministic or heuristic optimisation algorithms to achieve certain objectives, such as avoiding saturation of transformers, reducing GHG emissions, minimizing generation costs, etc. Besides, we can consider other objectives, such as minimizing transmission losses and maximizing the utilization of renewable energy sources (RES) [1].

TABLE 3. A summary of smart charging algorithms.

	Smart Charging Algorithm	Approach	Objective
1	Bayesian network (BN) based real-time EV charging scheduling [54]	The historical charging demand and PV generation output data are employed in forming the proposed optimisation model for attaining the optimal EV charging plan. Based on the traffic flow at the industrial park entrance and the statistics of daily driving mileage of EV users, the charging demand of EVs can be obtained. The EVCS coordinates with a rooftop PV facility. The historical power generation and meteorological data of surrounding PV facilities are collected to design the EV charging schedule.	The collected data and calculated results are used for training the BN to minimize the operation cost of EVCS.
2	A nonlinear programming (NLP) algorithm [9]	The optimisation is constrained by the condition of the operating buses, the electric vehicle supply equipment, and the power grid.	To minimize both the electricity cost and the battery aging.
3	Non-dominated sorted genetic algorithm (NSGA-II) [9]	Operating constraints (number of buses, initial SoC and battery temperature, the targeted SoC, arrival and departure time, maintenance period), charging station constraints (number of charging points, maximum charging power), and power grid constraints (time-of-use, power peak demand) are considered in the algorithm.	To minimize both the electricity cost and the battery aging.
4	Quadratic programming (QP) approach [37]	QP approach is an offline approach, where all events; cars arriving, departing, evolution of baseload of other electrical consumers are assumed to be known in advance.	To minimize the peak load and the load variability in a distribution grid.
5	Market based multi agent system (MAS) approach [37]	MAS will reflect the more realistic online situation, where we do not know beforehand what car will arrive, by when, but rather recompute the charging schedule dynamically upon arrival of each EV.	To minimize the peak load and the load variability in a distribution grid.
6	An energy-packet based (EPB) scheduling approach [38]	The SoC statistical distribution of the incoming vehicles and the patterns related to the vehicle's arrival time in parking areas are considered in the scheduling algorithm.	To minimize the peak power demand and maximize fully charged PEVs during their declared parking time.
7	A low-complexity online expected load flattening (ELF) algorithm based on model predictive control (MPC) [58]	Arrival time and the mean parking time are the parameters considered. Three different traffic patterns (light moderate and heavy traffic) are also considered.	To maximize load flattening
8	Online optimal charging strategy for multiple EV charging stations (based on the distributed MPC and modified convex relaxation techniques) [70]	Network information (power flow and bus voltage constraints), load & generation forecast for EV charging during the given time interval, and SoC are considered.	To optimally dispatch the charging schedule—this algorithm identifies the charging power for each charging station within the given time horizon.
9	Ant colony optimisation (ACO) algorithm for the smart charging strategy [11]	Graph of charging stations, charging station specifications, PEVs specifications, SoC, available number of sockets, queue status, price, and destination coordination are considered.	To find a station that ensures the minimum charging time, travel time, and charging cost.
10	Intelligent scatter search (ISS) algorithm based on a basic scatter search (SS) framework with advanced local solvers (deal with single EV charging) [57]	Multiple charging modes and diverse charging rate scenarios for distribution-side management are considered.	To minimize the charging cost or better cooperate with the system operator to smooth the load profile.
11	GA-ISS method comprised of GA theory and the proposed ISS approach for massive EV charging [57]	Battery parameters and charging behaviour, and the SoC of the battery are considered in the model. Multiple charging modes and diverse charging rate scenarios for distribution-side management.	To minimize the charging cost or better cooperate with the system operator to smooth the load profile.
12	Price-based smart charging algorithm [71]	Daily travel patterns and daily travel statistics are considered in this online control algorithm. The proposed charging algorithm can remotely monitor charging boxes, equipped with bi-directional communication devices and smart meters.	To balance the charging load and minimize the charging cost.

EV charge coordination can be classified broadly into three categories: 1) centralized, 2) hierarchical, and 3) decentralized. In centralized controlled strategy, a central controller has direct control over the charging time, charging duration and rates of vehicle charging actions on all participating EVs. Whereas in decentralized coordination strategy, each EV computes its charging events, avoiding the simultaneous charging of large numbers of EVs, that could destabilize the grid operation. Hierarchical coordination assumes the existence of an aggregator in a price-based charging mechanism [13].

Smart chargers that schedule EV charging based on demand, price, and other network constraints can shift the EV charging to high PV production periods and alleviate the minimum operational demand constraint [4]. Daily travelling distance, start time of the charging, capacity of the vehicles' battery, the SoC, and number of vehicles are considered as variables to build a charging model or charging profile in smart charging [55]. In situations where EV smart charging is insufficient to mitigate network constraints, other actions, such as utilization of onsite renewable energy, implementation of central storage facilities and relocating chargers to stronger parts of the network have to be implemented to avoid network reinforcements [41]. Table 3 summarises some of the smart charging approaches proposed in the literature.

E. SMART CHARGING: A DEMONSTRATION CASE STUDY

A 24-hour quasi-dynamic simulation was conducted to analyse the effectiveness of smart charging in improving the network performance with the same distribution network shown in Figure 2. Three load profiles shown in Fig. 10 are assigned randomly to all the customers in the distribution feeder shown in Fig. 2. As illustrated in load profiles, there are two peak load points in a day (around 8 am and around 7 pm).

The feeder voltage profiles with only loads are presented in Fig. 11. As shown in Fig. 11, bus voltage decreases at the peak load points, and the voltage drop is higher at downstream than the upstream of the feeder. During the day, the bus voltage remains in the range 0.94 ∼ 1.1. p.u. Fig. 12 shows the line loading in upstream of each phase. According to Fig. 12, closer to the peak load time, i.e., around 7 pm, it results in the maximum load, which is more than 90% of the rating of the line. The line load is relatively low during early morning (around 5am) and mid-day (around 1pm).

To investigate the effectiveness of smart charging, several assumptions were made on the daily travel distance of a vehicle, charging percentage, and arrival/ departure time of EV. Considering the average distance travel by a vehicle in Australia, USA, Netherlands, and Norway, 40 km was selected as the average daily travel distance for this simulation study [59]. Also, it is assumed that vehicle is fully charged (i.e. SoC is 100%) when it leaves home in the morning, and they get fully charged each day.

Also, this case study assumed three EVs in each phase, and they are located in T1, T8 and T15 in Fig. 2. Also, it is assumed that the EVs start charging at 6pm. The charging power of each EV is selected to be 3.4 kW, and it takes 2.2 hours to get fully charged [60]. The voltage and line loading are shown in Fig. 13 and Fig. 14, respectively. Obviously, the EV charging causes a voltage drop and increases the line loading during the evening time. The lowest voltage is recorded at T15, which is lower than 0.94 p.u., and the peak line loading is higher than 100%.

With the smart charging algorithm, the EV charging time is determined by the controller instead by the EV owner. The smart charging scheme adopted here will monitor the peak and the off-peak times and network constraints. Then the EV charging will be scheduled in off-peak time to flatten the demand profile during the day while ensuring the network voltage and thermal limits are not violated.

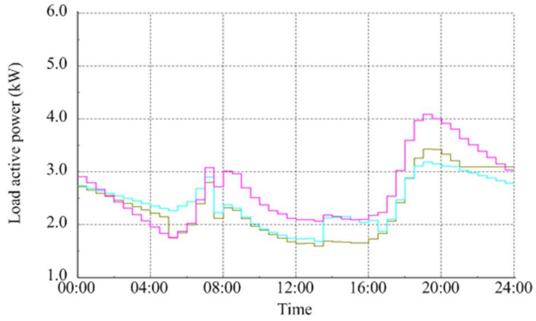

FIGURE 10. Load profiles.

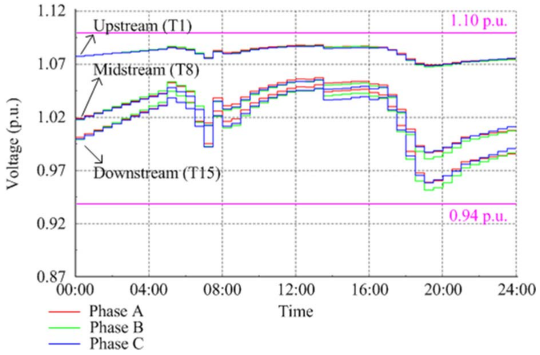

FIGURE 11. The voltage profiles with load only.

Once the smart charging scheme is implemented, EV charging starts from 4am, as shown in Fig. 15 and Figure 16. The line load increases from 50% to 70% during the charging time, and the voltage drops by a maximum value of 0.02 p.u. For the entire day, the bus voltage remains within 0.94 ∼ 1.1 p.u., and the line loading remains below 100%. The simulation results verify the effectiveness of the smart charging scheme in avoiding undervoltage and overload situations.

IV. RECOMMENDATIONS FOR PROMOTING SMART CHARGING

According to the published research and industry trials/ case studies, it is evident that the smart charging could bring a plethora of benefits to power grids. Therefore, government authorities, research institutions, utilities and the automotive industry should work together to establish policies and regulations to promote smart charging and reap benefits for power grids and EV owners. The key recommendations to promote smart charging are illustrated in Fig. 17.

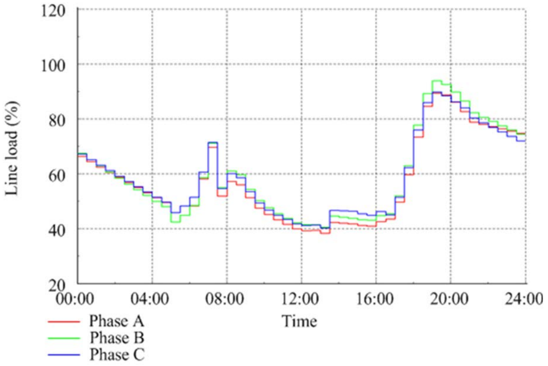

FIGURE 12. The line loading with load only.

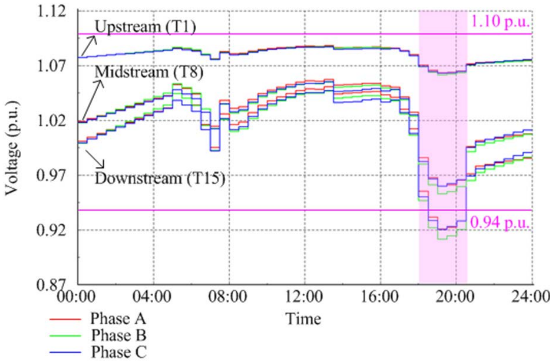

FIGURE 13. The voltage profiles with uncoordinated EV charging.

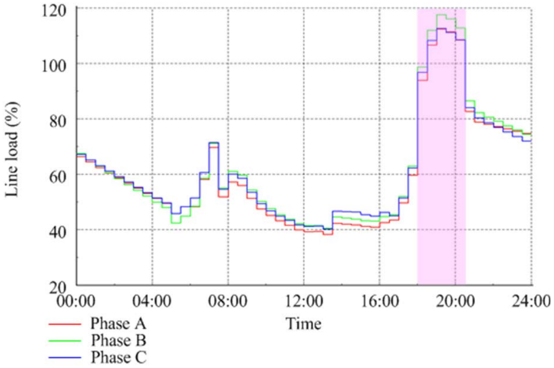

FIGURE 14. The line load with uncoordinated EV charging.

A. RECOMMENDATIONS ON REGULATORY FRAMEWORKS

Regulatory frameworks must be developed to promote smart charging and V2G across power networks. As demonstrated in the case study (Section III.E), the smart charging framework has considered the peak period, off-peak period and network conditions [2]. There will be more uptake in smart charging schemes when there are clear frameworks and rules around its usage. Therefore, appropriate regulatory frameworks should be designed by stipulating these functionalities for smart charging schemes.

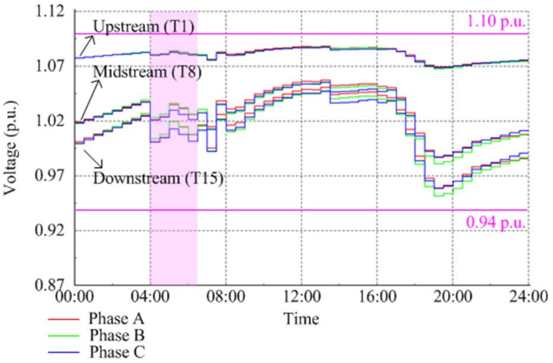

FIGURE 15. The voltage profiles with smart EV charging.

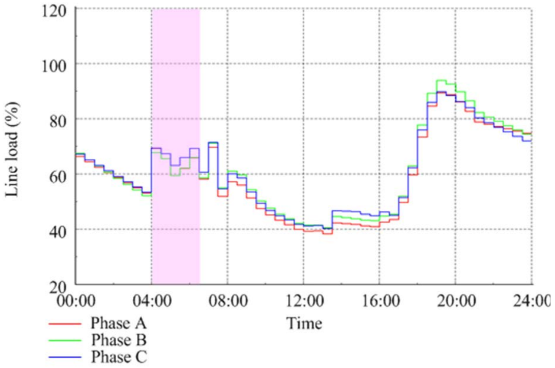

FIGURE 16. The line load with smart EV charging.

International Renewable Energy Agency (IRENA) has made some recommendations for framing the policies on smart charging, which includes: 1) implementation of smart charging islands in areas with high share of renewable energy sources; 2) design of smart charging strategies to fit the generation mix (solar, wind etc.); 3) standardize and ensure interoperability between EVs and supply equipment; 4) choose optimal locations for charging; 5) complement grid charging with storage at charging points or battery swapping; 6) support battery and charging research & development (R&D) considering both mobility and grid needs; 7) promote renewable energy to decarbonize power system and promote EVs to decarbonize the transport sector [2].

The following regulatory frameworks should be in place to ensure efficient deployment of smart-charging and V2G schemes;

- *Regulatory frameworks for smart charging infrastructure developers, owners and operators* – frameworks should include the off-peak times, peak-times, local network constraints, such as voltage and thermal limits of network assets,
- *Enabling revenue streams for smart charging and V2G users/ owners* – clear frameworks should be designed to enable regular revenue streams for the EV owners who are using smart charging and V2G schemes,

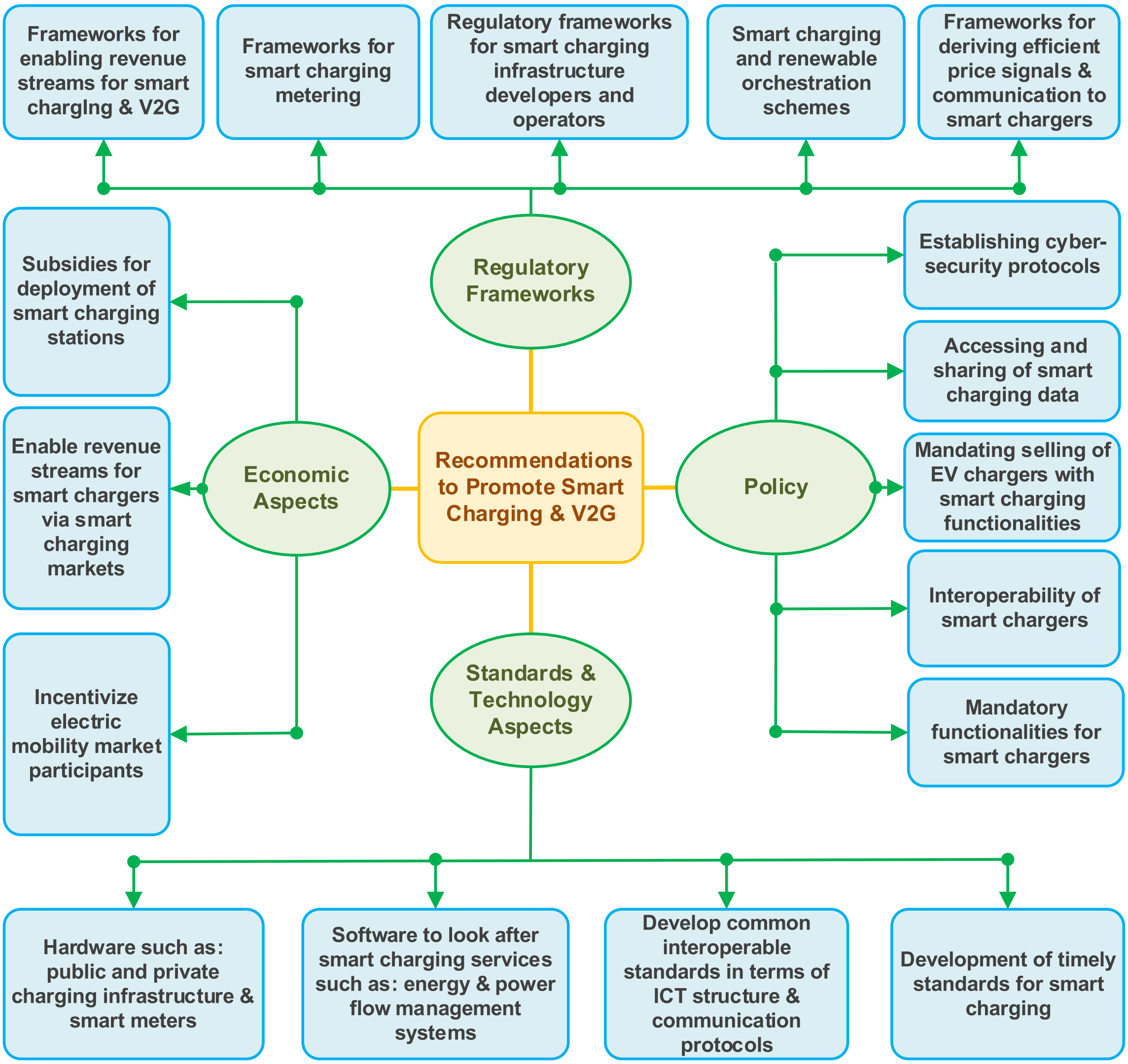

FIGURE 17. Recommendations for promoting smart charging.

- *Smart charging metering infrastructure* – smart charging infrastructure should be embedded with the smart meter infrastructure to accurately measure the energy associated with the smart charging and V2G,
- *Orchestration technologies* – Smart charging and V2G technologies can be orchestrated with variable renewable energy technologies to maximize the benefits, but appropriate regulatory frameworks should be designed with orchestration technologies,
- *Deriving efficient price signals* – Regulatory schemes can be implemented for deriving efficient price signals to enable smart charging.

B. GENERAL POLICY RECOMMENDATIONS

European policies, such as Electricity Market Directive 2019/44 aimed at removing barriers to manage their grids and actively provide flexibility. However, more progress on smart charging needs to be made in other European Union (EU) policies, for example, the Alternative Fuel Infrastructure (AFI) directive (AFI Directive 2014/94/EU). AFI directive has been revised to accommodate smart charging. Therefore, existing policies should be updated to support the increasing number of EVs and the associated infrastructure [61].

One of the critical policy directives implemented in UK was mandating smart charging functionalities for all EV chargers sold in the UK [62]. This has enabled the availability of one of the critical EV smart charging infrastructure assets across the network. Similarly, the exiting EV owners should be encouraged to upgrade their EV charging assets by providing subsidies to them. Also, the UK has adopted a phased approach to implement smart charging, and it is driven by four main objectives: 1) consumer uptake, 2) consumer protection, 3) grid stability, and 4) innovation [63]. The following are the other smart charging policy recommendations implemented in the UK [63];

- Smart chargers should be interoperable, and hence they should be compatible with all energy supplies,

- EV owners/ drivers should set smart charging schedules and preferences not to allow charging during the peak periods,
- Define mandatory functionalities for energy monitoring and metering at the smart chargers,
- Enabling cyber-security protocols for smart charging infrastructure to ensure data privacy and security, such as PAS 18978/1879 by British Standards Institution (BSI),
- Ensure grid stability and safety by mandating enhanced functionalities for smart chargers (e.g. random delay functions, emergency power off),
- Penalties for non-compliant chargers,
- Accessing and sharing of EV charging data for prudent operational and planning decision making.

In addition, as smart charging could be controlled via control signals, they should also be considered under the umbrella of demand-side response (DSR) schemes/ devices for providing system flexibility etc. The "Electric Nation project" in the UK demonstrated the potential of smart charging as a resource that could unlock system flexibility in a two-year field trial conducted with 700 EV drivers [64]. Therefore, the policies around DSR should be augmented to facilitate the inclusion of smart charging as a DSR service.

Similar to smart charging, it is recommended to strengthen the support mechanisms for V2G, as this technology could complement smart charging and increase the renewable energy penetration in the power grid. Development of algorithms to minimize the technical impacts and to maximize privacy and security are required under V2G privacy standards. When developing regulations for V2G, priority must be given to increase the research towards improving the degradation of batteries and enhance charging efficiency. This can be achieved by initiating pilot projects and giving access to the data, and this will enable opportunities to test algorithms and obtain insight on battery degradation. That would ultimately assist in developing improved battery management systems that can reduce the battery degradation and costs associated with the V2G.

C. ECONOMIC POLICY RECOMMENDATIONS

The economic policies to promote smart charging and V2G should focus on providing financial incentives to the EV owners and charging infrastructure owners. European Environmental Citizens' Organization for Standardization (ECOS) recommends creating incentives for public or semi-public parking lot operators and owners [61]. Governments and local authorities in emerging EV markets should also design incentives for smart charging and provide subsidies for promoting smart chargers and smart charging infrastructure. For example, in United Kingdom, from July 2019, only home charging points that use 'smart charging' technology are eligible for government funding under the 'Electric Vehicle Home Charge Scheme' [65].

One of the key aspects that should be implemented with smart charging is 'time-of-use tariffs.' Eventually, dynamic prices for EV charging will allow EVs to participate in the ancillary services market, which enables value stacking, and avoid doubling the cost [2]. It also creates an additional revenue stream for EV owners. In addition, appropriate business models must be developed to promote smart charging among EV fleets, and EV mass charging infrastructure operators [66].

V. OTHER TECHNICAL ASPECTS AND RECOMMENDATIONS

Along with policies, the development of international standards and communication protocols are of paramount importance for increasing the smart charging uptake. In many instances, electrotechnical issues, such as plugs, outlets, and electrical safety, are focused when developing standards, but to ensure compatibility and seamless communication between charging points, electricity distribution networks and electric vehicles, communication interfaces and data models also need to be standardized. Many studies have pointed out the importance of standardizing the communication protocols used in EV charging and the importance of interoperability of charging control systems and charging stations [67]. Standardization of communication protocols is essential, since the smart charging stations and control systems have to be interoperable [4]. Therefore, standardization is essential to effectively integrate EVs into the power grid [68].

A. TECHNICAL STANDARDS

At present, there are only a few standards available supporting smart charging. These standards include charging standards at the vehicle end, and system standards and rules at the grid end. It is unlikely that these standards will improve at a similar pace with the increasing uptake of EVs. Key technical pieces for smart charging infrastructure are hardware, such as chargers and compatible vehicles; software, such as orchestration platforms; standards, to ensure compatibility of the system components [15]. At the international level, Europe has made significant efforts to standardize the smart charging to accomplish an interoperable, seamless, and secure systems [4]. To attain the full potential of smart charging, ECOS strongly recommends proceeding with the smart charging standardization process, which holds up the EU regulatory requirements for smart charging [61].

To support "all smart charging scenarios" new standards are being developed or revised or still under development within the international and the European standardization organizations, such as the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the European body CENELEC [61]. IEC 61851 on "Electric Vehicle Technologies" defines safety rules for charging with plugs and cables (AC or DC) and the necessary low-level communication between the charging station and the EV, whereas ISO 15118 on "Road vehicles — Vehicle to grid communication interface" defines a high-level communication between a charging station and an EV for the control of charging services on top of IEC 61851 [61], [69].

The new standard, known as ISO 15118-20 "2nd generation network and application protocol requirements," will deliver the important features required for smart charging, and will enable all smart charging scenarios [61], [68].

To cover the remainder of charging infrastructure, another standardization project, IEC 63110 "Charging Station Management," was launched in 2017. The goal is to define the remote management of charging stations by their operators and the integration with energy management systems [68]. Moreover, IEC 63119 "Charging Service Providers" will be the international standard for roaming and payment in the context of EV charging services [61], [68], [51]. At the European level, the standard CSN EN 50549 is a newly revised standard with requirements for generating plants to be connected in parallel with distribution networks. Within the same family, the standard CLC EN 50491-12 "Smart grid interface" is currently under development to define control types for the energy management inside buildings, and will also has an alignment with the EV charging standards which are going to be published in future [61].

Although these technical standard development activities are in progress, more standardization work is still required on interoperability area to ensure smart chargers, and infrastructure are compatible with any standardized hardware and equipment of the energy supplier.

B. COMMUNICATION PROTOCOLS TO SUPPORT SMART CHARGING

Smart charging system comprises a bidirectional communication channel between two or more facilities to optimize all customer necessities as well as managing the reliability and safety of the power grid (see Figure 9) [2]. Communication protocols offer a set of rules and guidelines for effective charging demand supervision, grid integration of EVs, and enabling communication and data exchange between facilities [68]. Universally adaptable, secure, and reliable end-to-end communication is necessary for EV network applications. Therefore, the development of effective communication protocols is essential to optimize the charging and facilitate information sharing.

To communicate between EV charging stations and the charging station management system (CSMS), open charge point protocol (OCPP) is developed by the Open Charge Alliance [4]. CSMS is managed by the company which operates the charging station, and it is a cloud-based backend system. Besides the consideration of generation and grid constraints, to make sure that the customers benefit from the dynamic price opportunities, control signals can be communicated through an information and communications technology (ICT) infrastructure [2]. To communicate between a charge point management system and an energy management system, open smart charging protocol (OSCP) and to permit boundless electric vehicle charging across charging station networks, the open clearing house protocol (OCHP) are used in [69]. By means of OCHP, e-Mobility service providers can connect to EV charging operators and providers to offer the network access.

The open inter charge protocol (OICP) developed by Hubject and eMIP is a communication standard implemented between e-mobility service provider (EMSP) and charge point operator (CPO) systems through the Hubject platform. It enables reliable information exchange with electric car drivers. E-Mobility interoperation protocol (eMIP), designed by GIREVE, enables roaming of charging services by providing a charge authorization and a data clearing house application programming interface (API) and access to a comprehensive charging point database [3], [15], [68].

These communication protocols enable smart charging possible, however for wide-scale adaptation of these charging protocols, it is essential to develop suitable policies to mandate the interoperable communication protocols which offer smart charging functionalities.

VI. CONCLUSION AND POLICY IMPLICATIONS

In this paper, we critically reviewed the effects of uncoordinated EV charging and V2G on power grids, and also demonstrated the adverse effects of unmanaged EV charging and V2G on power distribution networks via simulation case studies. Simulation case studies have demonstrated the impact on the distribution network voltage profile, line loading and network unbalance due to uncoordinated charging of EVs. Subsequently, we demonstrated the benefits of smart coordinated charging via quasi-dynamic simulations. In particular, the effectiveness of the smart charging was illustrated by flattening the load profile and avoiding undervoltage and overload conditions in distribution feeders. Moreover, smart charging will also assist in achieving the decarbonizing targets in power systems by enabling high renewable power penetration levels.

The smart charging studies and smart charging trial outcomes have revealed that smart charging can bring a wide variety of financial, economic, and environmental benefits. The study also found that some jurisdictions have made a significant progress towards smart charging via policy mandates, but still majority of the jurisdictions are yet to embrace or mandate smart charging for EVs. Therefore, to successfully implement smart charging, policy, regulatory frameworks, and other technical aspects should be implemented across the entire EV charging eco-system.

REFERENCES

[1] S. Habib, M. M. Khan, F. Abbas, L. Sang, M. U. Shahid, and H. Tang, "A comprehensive study of implemented international standards, technical challenges, impacts and prospects for electric vehicles," *IEEE Access*, vol. 6, pp. 13866–13890, 2018, doi: 10.1109/ACCESS.2018.2812303.

[2] *Electric-Vehicle Smart Charging—Innovation Landscape Brief*, International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 2019, pp. 1-24.

[3] *Global EV Outlook 2020 Entering the Decade of Electric Drive?*, IEA, Paris, France, 2020.

[4] *Innovation Outlook: Smart Charging for Electric Vehicles*, International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 2019.

[5] *Future Energy Scenarios*, National Grid UK, London, U.K., Jul. 2021. [Online]. Available: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021/scenarios-net-zero

[6] AEMO. (2017). *2017 Electricity Forecasting Insights*. Accessed: Oct. 7, 2020. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/demand-forecasts/efi/2017-electricity-forecasting-insights.pdf?la=en&hash=396E33DF3FC62B70F41CBFC35B49CF87

[7] Energeia. (2017). Electric Vehicles Insights. AEMO. Accessed: Oct. 7, 2020. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/demandforecasts/efi/2018/final—aemo-ev-insights—september-2017.pdf

[8] B. Sturmberg. (2000). Are 19 Million Electric Vehicle Batteries Equal to Five Snowy 2.0S? Renew Economy. Accessed: Sep. 16, 2020. [Online]. Available: https://reneweconomy.com.au/are-19-million-electric-vehicle batteries-equal-to-five-snowy-2-0s-61400/

[9] A. Houbbadi, E. Redondo-Iglesias, R. Trigui, S. Pelissier, and T. Bouton, ''Optimal charging strategy to minimize electricity cost and prolong battery life of electric bus fleet,'' in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Oct. 2019, pp. 1–6, doi: 10.1109/VPPC46532.2019.8952493.

[10] S. Limmer, ''Dynamic pricing for electric vehicle charging—A literature review,'' *Energies*, vol. 12, no. 18, p. 3574, Sep. 2019.

[11] Z. Moghaddam, I. Ahmad, D. Habibi, and Q. V. Phung, ''Smart charging strategy for electric vehicle charging stations,'' *IEEE Trans. Transport. Electrific.*, vol. 4, no. 1, pp. 76–88, Mar. 2018, doi: 10.1109/TTE.2017.2753403.

[12] K. Qian, C. Zhou, M. Allan, and Y. Yuan, ''Modeling of load demand due to EV battery charging in distribution systems,'' *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 802–810, Mar. 2010.

[13] Z. Wang and R. Paranjape, ''An evaluation of electric vehicle penetration under demand response in a multi-agent based simulation,'' in *Proc. IEEE Electr. Power Energy Conf.*, Nov. 2014, pp. 220–225.

[14] L. Jones, K. Lucas-Healey, B. Sturmberg, H. Temby, and M. Islam, ''ANU ARENA Project: A comprehensive analysis of vehicle-to-grid technology worldwide,'' Austral. Nat. Univ., Canberra, ACT, Australia,

[15] D. Hall and N. Lutsey, ''Literature review on power utility best practices regarding electric vehicles,'' International Council on Clean Transportation, San Francisco, CA, USA, Tech. Rep., 2017. [Online]. Available: https://www.theicct.org

[16] M. S. Alam, M. Shafiullah, M. J. Rana, M. S. Javaid, U. B. Irshad, and M. A. Uddin, ''Switching signal reduction of load aggregator with optimal dispatch of electric vehicle performing V2G regulation service,'' in *Proc. Int. Conf. Innov. Sci., Eng. Technol. (ICISET)*, Oct. 2016, pp. 1–4, doi: 10.1109/ICISET.2016.7856491.

[17] A. Chitkara, D. Cross-Call, B. Li, and J. Sherwood, ''A review of alternative rate designs: Industry experience with time-based and demand charge rates for mass-market customers,'' Mountain Institute, Basalt, Colorado, USA, RMI, Tech. Rep., 2016, [Online]. Available: https://rmi.org/wp-content/uploads/2017/04/A Review-of-Alternative-Rate-Designs-2016.pdf

[18] McKinsey. *How Electric Vehicles Could Change the Load Curve*. [Online]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-potential-impact-of-electric-vehicles-on-global-energy-systems

[19] M. T. Hussain, D. N. B. Sulaiman, M. S. Hussain, and M. Jabir, ''Optimal management strategies to solve issues of grid having electric vehicles (EV): A review,'' *J. Energy Storage*, vol. 33, Jan. 2021, Art. no. 102114, doi: 10.1016/j.est.2020.102114.

[20] G. Sharma and V. K. Sood, ''Power quality problems in grid-connected electric vehicle (EV) fast charging stations,'' in *Recent Advances in Power Electronics and Drives*. Singapore: Springer, 2021, pp. 11–27, doi: 10.1007/978-981-15-8586-9_2.

[21] A. Dubey and S. Santoso, ''Electric vehicle charging on residential distribution systems: Impacts and mitigations,'' *IEEE Access*, vol. 3, pp. 1871–1893, 2015, doi: 10.1109/ACCESS.2015.2476996.

[22] A. S. Masoum, S. Deilami, P. S. Moses, M. A. S. Masoum, and A. Abu-Siada, ''Smart load management of plug-in electric vehicles in distribution and residential networks with charging stations for peak shaving and loss minimisation considering voltage regulation,'' *IET Generat., Transmiss. Distrib.*, vol. 5, no. 8, pp. 877–888, Aug. 2011.

[23] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, ''Voltage profile and THD distortion of residential network with high penetration of plug-in electrical vehicles,'' in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT Europe)*, Oct. 2010, pp. 1–6.

[24] R. Bass and N. Zimmerman, ''Impacts of electric vehicle charging on electric power distribution systems,'' Portland State University, Portland, OR, USA, Tech. Rep. OTREC-SS-731, 2013.

[25] G. Hoogsteen, ''Charging electric vehicles, baking pizzas and melting a fuse in Lochem,'' in *Proc. 24th Int. Conf. Electr. Distrib. (CIRED)*, Glasgow, Jun. 2017, pp. 1629–1633.

[26] L. Pieltain Fernández, T. Gómez San Román, R. Cossent, C. Mateo Domingo, and P. Frías, ''Assessment of the impact of plug-in electric vehicles on distribution networks,'' *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 206–213, Feb. 2011, doi: 10.1109/TPWRS.2010.2049133.

[27] J. R. Pillai and B. Bak-Jensen, ''Integration of vehicle-to-grid in the western Danish power system,'' *IEEE Trans. Sustain. Energy*, Jan. 2010, Art. no. 5560848, doi: 10.1109/TSTE.2010.2072938.

[28] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, ''Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile,'' *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011, doi: 10.1109/TSG.2011.2159816.

[29] E. Taibi, C. Fernández, and I. Innovation, ''The impact of electric vehicles deployment on production cost in a Caribbean Island country,'' in *Proc. 1st E-Mobility Power Syst. Integr. Symp.*, Berlin, Germany, Oct. 2017, p. 8.

[30] Electric Nation. (2019). *My Electric Nation Trial*. [Online]. Available: https://www.electricnation.org.uk/wp-content/uploads/2019/07/Electric-Nation-Trial-Summary-A4.pdf

[31] C. Z. El-Bayeh, K. Alzaareer, A.-M.-I. Aldaoudeyeh, B. Brahmi, and M. Zellagui, ''Charging and discharging strategies of electric vehicles: A survey,'' *World Electric Vehicle J.*, vol. 12, no. 1, p. 11, Jan. 2021, doi: 10.3390/wevj12010011.

[32] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do, and J.-W. Jung, ''Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration,'' *Renew. Sustain. Energy Rev.*, vol. 34, pp. 501–516, Jun. 2014, doi: 10.1016/j.rser.2014.03.031.

[33] B. Zeng, J. Feng, J. Zhang, and Z. Liu, ''An optimal integrated planning method for supporting growing penetration of electric vehicles in distribution systems,'' *Energy*, vol. 126, pp. 273–284, May 2017, doi: 10.1016/j.energy.2017.03.014.

[34] M. Yilmaz and P. T. Krein, ''Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces,'' *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5673–5689, Dec. 2013, doi: 10.1109/TPEL.2012.2227500.

[35] H. Lund and W. Kempton, ''Integration of renewable energy into the transport and electricity sectors through V2G,'' *Energy Policy*, vol. 36, no. 9, pp. 3578–3587, 2008, doi: 10.1016/j.enpol.2008.06.007.

[36] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, ''Integration of electric vehicles in the electric power system,'' *Proc. IEEE*, vol. 99, no. 1, pp. 168–183, Jan. 2011, doi: 10.1109/JPROC.2010.2066250.

[37] K. Mets, R. D'hulst, and C. Develder, ''Comparison of intelligent charging algorithms for electric vehicles to reduce peak load and demand variability in a distribution grid,'' *J. Commun. Netw.*, vol. 14, no. 6, pp. 672–681, Dec. 2012.

[38] G. Graber, G. Massa, V. Galdi, V. Calderaro, and A. Piccolo, ''Performance comparison between scheduling strategies for PEVs charging in smart grids,'' in *Proc. Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Nov. 2015, pp. 1213–1218, doi: 10.1109/ICRERA.2015.7418601.

[39] S. Deb, K. Tammi, K. Kalita, and P. Mahanta, ''Impact of electric vehicle charging station load on distribution network,'' *Energies*, vol. 11, no. 1, p. 178, 2018, doi: 10.3390/en11010178.

[40] D. Hilson. (2019). Managing the Impacts of Renewably Powered Electric Vehicles on Electricity Distribution Networks. EVENERGI. [Online]. Available: https://arena.gov.au/assets/2019/03/managing-the-impacts-of-renewably-powered-electric-vehicles-on-distribution-networks.pdf

[41] Florence School of Regulation. (Feb. 2020). *Access to Electric Vehicles Data for Smart Charging*. [Online]. Available: https://fsr.eui.eu/access-to-electric-vehicles-data-for-smart-charging/

[42] Electric Nation Project. (Oct. 2019). *Summary of the Findings of the Electric Nation Smart Charging Trial*. [Online]. Available: https://www.electricnation.org.uk/wp-content/uploads/2019/07/Electric-Nation-Trial-Summary-A4.pdf

[43] (2020). *INVADE Horizon*. [Online]. Available: http://h2020invade.eu

[44] INVADE Horizon (2020). *The Netherlands*. [Online]. Available: https://h2020invade.eu/the-project/the-Netherlands/

[45] ARENA. (2015). *Origin Energy Electric Vehicles Smart Charging Trial*. [Online]. Available: https://arena.gov.au/projects/origin-energy-electric-vehicles-smart-charging-trial

[46] SP Energy Networks. *Charge: Refuelling Tomorrow's Electrified Transport*. [Online]. Available: https://www.spenergynetworks.co.uk/pages/charge.aspx

[47] The Parker Project. (2019). *The Parker Project Final Report*. [Online]. Available: https://parker-project.com/wp-content/uploads/2017/03/Danish-project-defines-the-electricvehicle-of-the-future.pdf

[48] L. Noel, A. Papu Carrone, A. F. Jensen, G. Zarazua de Rubens, J. Kester, and B. K. Sovacool, "Willingness to pay for electric vehicles and vehicle-to-grid applications: A Nordic choice experiment," *Energy Econ.*, vol. 78, pp. 525–534, Feb. 2019, doi: 10.1016/j.eneco.2018.12.014.

[49] K. Knezović, M. Marinelli, A. Zecchino, P. B. Andersen, and C. Traeholt, "Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration," *Energy*, vol. 134, pp. 458–468, Sep. 2017, doi: 10.1016/j.energy.2017.06.075

[50] L. Noel, G. Z. de Rubens, J. Kester, and B. K. Sovacool, "History, definition, and status of V2G," in *Vehicle-to-Grid*. Cham, Switzerland: Springer, 2019, pp. 1–31, doi: 10.1007/978-3-030-04864-8_1.

[51] L. Noel, G. Zarazua de Rubens, J. Kester, and B. K. Sovacool, "Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)," *Transp. Policy*, vol. 71, pp. 130–137, Nov. 2018, doi: 10.1016/j.tranpol.2018.08.004.

[52] X. Li, Y. Tan, X. Liu, Q. Liao, B. Sun, G. Cao, C. Li, X. Yang, and Z. Wang, "A cost-benefit analysis of V2G electric vehicles supporting peak shaving in Shanghai," *Electric Power Syst. Res.*, vol. 179, Feb. 2020, Art. no. 106058, doi: 10.1016/j.epsr.2019.106058.

[53] J. A. P. Lopes, F. J. Soares, P. M. Almeida, and M. M. Silva, "Smart charging strategies for electric vehicles: Enhancing grid performance and maximizing the use of variable renewable energy resources," in *Proc. EVS24 Int. Battery, Hybrid Fuel Cell EV Symp.*, May 2009, pp. 1–11.

[54] H. Ren, F. Wen, C. Xu, J. Du, and J. Tian, "Bayesian network based real-time charging scheduling of electric vehicles," in *Proc. Int. Conf. Smart Grids Energy Syst. (SGES)*, Nov. 2020, pp. 1022–1026, doi: 10.1109/SGES51519.2020.00186.

[55] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 82–102, Apr. 2013, doi: 10.1016/j.rser.2012.11.077.

[56] C. M. G. D. Almeida, (2019). Smart Charging of EV Batteries for Load Balancing Strategies. Royal Institute of Technology. [Online]. Available: http://www.diva-portal.org/smash/get/diva2:1372599/FULLTEXT01.pdf

[57] T. Mao, X. Zhang, and B. Zhou, "Intelligent energy management algorithms for EV-charging scheduling with consideration of multiple EV charging modes," *Energies*, vol. 12, no. 2, p. 265, Jan. 2019.

[58] W. Tang and Y. J. Zhang, "A model predictive control approach for low-complexity electric vehicle charging scheduling: Optimality and scalability," *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 1050–1063, Mar. 2017, doi: 10.1109/TPWRS.2016.2585202.

[59] Enel X. *How Far Can Electric Cars Go On One Charge?*. Accessed: Aug. 15, 2021. [Online]. Available: https://evcharging.enelx.com/resources/blog/666-how-far-can-electric-cars-go-on-one-charge

[60] Car Sales. *How Long Does It Take to Charge An EV?*. Accessed: Aug. 15, 2021. [Online]. Available: https://www.carsales.com.au/editorial/details/how-long-does-it-take-to-charge-an-electric-vehicle-123022/

[61] *Electric Vehicle Smart Charging: The Key to A Renewable and Stable Grid*, ECOS EU, Brussels, Belgium, 2020.

[62] U.K. Legislation. *Automated and Electric Vehicles (AEV) Act 2018*. Accessed: Mar. 23, 2022. [Online]. Available: https://www.legislation.gov.uk/ukpga/2018/18/contents/enacted

[63] *Electric Vehicle Smart Charging/–Government Response to the 2019 Consultation on Electric Vehicle Smart Charging*, HM Government, London, U.K., Jul. 2021.

[64] Electric Nation, "The flexibility of domestic electric vehicle charging," The Electric Nation Project, IEEE PES Magazine, 2021.

[65] RECC. *2019—Annual Report—Scheme—Renewable Energy Consumer Code (RECC)*. Accessed: Aug. 15, 2021. [Online]. Available: https://www.recc.org.uk/scheme/annual-report/2019

[66] ENSTO. *5 Great EV Charging Business Models*. [Online]. Available: https://www.ensto.com/company/newsroom/blogs/5-greatev-charging-business-models/

[67] *The Future of Electric Vehicle Smart Charging*, Engage Consulting Limited, Energy U.K., London, U.K., Apr. 20210.

[68] M. Neaimeh and P. B. Andersen, "Mind the gap- open communication protocols for vehicle grid integration," *Energy Informat.*, vol. 3, no. 1, Dec. 2020, doi: 10.1186/s42162-020-0103-1.

[69] I. S. Bayram and I. Papapanagiotou, "A survey on communication technologies and requirements for Internet of Electric vehicles," *EURASIP J. Wireless Commun. Netw.*, vol. 2014, no. 1, p. 223, Dec. 2014, doi: 10.1186/1687-1499-2014-223.

[70] Y. Zheng, Y. Song, D. J. Hill, and K. Meng, "Online distributed MPC-based optimal scheduling for EV charging stations in distribution systems," *IEEE Trans. Ind. Informat.*, vol. 15, no. 2, Feb. 2019.

[71] B. Wang, B. Hu, C. Qiu, P. Chu, and R. Gadh, "EV charging algorithm implementation with user price preference," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, 2015, pp. 1–5, doi: 10.1109/ISGT.2015.7131895.

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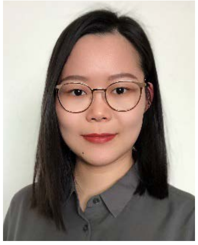

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