A Review on Electric Vehicle Charging Infrastructure Development in the UK

Tianjin Chen, Xiao-Ping Zhang, Jianji Wang, Jianing Li, Cong Wu, Mingzhu Hu, and Huiping Bian

***Abstract*—This paper focuses on the development of electric vehicle (EV) charging infrastructure in the UK, which is a vital part of the delivering ultra-low-emission vehicle (ULEV) and will transition into low emission energy systems in the near future. Following a brief introduction to global landscape of EV and its infrastructure, this paper presents the EV development in the UK. It then unveils the government policy in recent years, charging equipment protocols or standards, and existing EV charging facilities. Circuit topologies of charging infrastructure are reviewed. Next, three important factors to be considered in a typical site, i.e., design, location and cost, are discussed in detail. Furthermore, the management and operation of charging infrastructure including different types of business models are summarized. Last but not least, challenges and future trends are discussed.**

***Index Terms*—Electric vehicle (EV), charging point, charging infrastructure, smart charging.**

I. Introduction

CLIMATE change poses a great challenge to the sustainable development of human civilization. Governments around the world are working to reduce carbon emissions, of which road transport tend to account for a significant proportion. As a result, vehicle emission targets have been put in place in many countries. Electric vehicles (EVs) featured as environmentally friendly have thus got extensive attention in recent years [1]-[3]. According to [4], the total sale number of global EVs reached 3 million by 2017. With more than half of the global sales contributed by China, over 1 million EVs were sold in 2017, which was over 50% increase from 2016. In the meantime, nearly 40% of new vehicles registered in Norway were EVs in 2017, followed by Iceland with 11.7% and Sweden with 6.3%. Rapid developments in battery production technology with higher energy density, higher number of charge cycles, better safety and lower cost enable the ever increasing EV uptakes. Furthermore, EV sales worldwide are primarily driven by policies targeting at low-emission transport and energy consumption. Taking into account the existing and announced policies, the estimated so-called New Policies Scenarios will be 125 million EVs on the road by 2030. More aggressive EV30@30 scenarios, which estimate 30% of global sales share of road transport will be EVs by 2030, have an ambitious target of 228 million EVs. This goal is in line with the Paris Agreement.

Meanwhile, with the rapid development of EV, its supply equipment or charging infrastructure is essential. Apart from the technological innovation of EV, effective charging infrastructure plays a fundamental role in supporting the wider adoption of EV. By 2017, it has been estimated that there were about 430 thousand public chargers globally [4]. Over 100 thousand of them are fast chargers. In comparison, there were nearly 3 million private chargers for homes and workplaces in 2017. Considering the projection of EVs by 2030, worldwide electricity consumption from EVs reaches 400 TWh in the New Policies Scenarios and 928 TWh in the EV30@30 scenarios, which are 7 times and 17 times increase compared to 2017, respectively, [4]. It is suggested that around 130 million private chargers and 13 million public chargers need to be installed by 2030. Potentially, this is a massive market globally with billions of investment in infrastructure.

In the UK, the government has aggressive emission targets by 2030 and 2050. It is convinced that the majority of greenhouse gas emission is contributed by transport [5]. The UK government has therefore established an ambitious roadmap to be world leader in EV design, development and manufacture, and to be one of the most attractive locations for EV-related inward investment in the world [6], [7]. This paper focuses on EV infrastructure development in the UK, including the landscape of EV, incentive schemes for EV and its charging infrastructure, charging standards, and the statistics of existing facilities. Moreover, typical design and business model of EV charging infrastructure will also be discussed. Last but not least, this paper will present emerging challenges for the development of EV and its charging infrastructure.

II. EVs in the UK

The UK government initially published an ultra-low emission vehicle (ULEV) strategy to encourage the growth in the

Manuscript received: June 13, 2018; accepted: August 12, 2019. Date of CrossCheck: August 12, 2019. Date of online publication: March 9, 2020.

This work is from a research project in collaboration with and sponsored by XU JI Power Co., Ltd., Xuchang, China.

T. Chen, M. Hu and H. Bian are with XU JI Power Co., Ltd., Xuchang, China (e-mail: chentianjindy@126. com; winhmz@163. com; bianhuipingdy@126. com).

X.-P. Zhang (corresponding author), J. Li and C. Wu are with the Department of Electronic, Electrical and Systems Engineering, University of Birmingham, Birmingham, UK (e-mail: x.p.zhang@bham.ac.uk; j.li.6@bham.ac.uk; cxw752 @student.bham.ac.uk).

J. Wang is with State Grid Shandong Electric Power Company, Linyi, China (e-mail: 583632942@qq.com).

DOI: 10.35833/MPCE.2018.000374

ULEV market in 2009. The ULEVs are the vehicles that emit less than 75 g of CO_2 per kilometer travelled, the vast majority of which are hybrid electric or pure electric. A strategy called "Driving the Future Today" was published in September 2013 and committed to cutting carbon emissions from transport, aiming at zero emission for nearly all cars and vans by 2050. The key elements of the proposed package for supporting ULEVs during 2015-2020 were set out in the following year [8]. The Automated and Electric Vehicles Bill 2017-2019 was introduced in the House of Commons in October 2017, which also intended to help deliver the zero-emission aim of 2050 [9].

The government has continuously published some grant schemes to incentivize the development of EVs as well. The grant for plug-in cars and vans was launched in 2011 and the grant structure has reformed since March 2016 [10], [11]. The price will get reduced by grants when buyers pay for EVs approved by the government. EVs are categorized into several groups and the allocated grant relies on the category of EV [12]. In October 2016, the government committed an additional £4 million to the plug-in van grant scheme, extending the eligibility to larger electric trucks.

For electric buses and taxis, the grant schemes were initially announced in April 2014, and the details of the scheme were published in March 2015 [8]. Also, the government confirmed a £150 million boost to support cleaner buses and taxis in November 2016 [13]. In March 2017, a further £64 million was available to support two schemes related to plug-in taxis [14].

Furthermore, both private and business users of ULEVs receive a number of tax benefits ranging from fuel duty, vehicle excise duty (VED) and value added tax (VAT) that are applicable to all ULEV users to the taxation of company cars (CCT) and benefit charges for business users only. For example, regarding VAT, the electricity used to recharge a plug-in vehicle at home attracts only 5% level of VAT, much lower than road fuels (20%) [15].

New ULEV registrations and their percentage of all new registrations are shown in Fig. 1. During 2017, 53203 new ULEVs were registered for the first time in the UK, a 27% increase from 41837 in 2016. This accounted for 1.7% of all new vehicle registrations, up from 1.2% one year before and 0.9% two years before. New registrations of ULEVs have been rapidly increasing since 2014 [16]. In [17] and Tabel I, it is estimated that by 2040, the market size for the whole Great Britain (GB) system is massive. The annual energy demand could reach 11 to 15 TWh with the total equipment and installation cost of £2 billion.

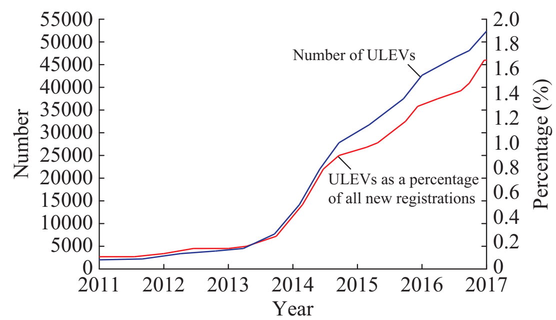

Fig. 1. New ULEV registrations in the UK from 2011 to 2017.

TABLE I
SUMMARY OF MARKET SIZING ESTIMATES IN GB, 2040

Application	Usage	Annual energy (TWh)	Outlet	Cost of charger (billion £)
Workplace commuters	12 million cars, 182 visits/year, 7.6 h/visit	5.9-8.3	900000-2400000	1.6-4.4
Fleet vans	0.6 million cars, 254 visits/year, 12 h/visit	2.6-3.4	300000-600000	0.7-1.3
Public car parks	33 million cars, 164 visits/year, 2.3 h/visit	1.8-2.4	40000-110000	0.1-0.2
Motorway	99 billion cars & vans miles/year	0.7-0.9	1000-8000	0.1-0.2
Total		11.0-15.0	1000000-3000000	2.0-6.0

III. INCENTIVES, STANDARDS AND STATISTICS OF EV INFRASTRUCTURE

In addition to making EV more affordable, the effective charging infrastructure network is another fundamental part to enable further promotion and wider use of EVs across the country. The government incentives and technical standards of the charging infrastructure are discussed below.

A. Government Strategy for EV Infrastructure

The development of EV infrastructure has been encouraged since 2009 [6], [18], [19]. A government strategy for plug-in vehicle infrastructure called "Making the Connection" was published in 2011, which set the development framework of recharging infrastructure to support EV owners and industry in the UK, and aimed to stimulate the growth of EV market [20]. In 2014, the Alternative Fuel Infrastructure Directive was agreed by the European Union (EU), and the UK is legally bound to implement the requirements although having voted to leave the EU in June 2016 [21], [22]. Besides, the Bill in October 2017 allowed the government to regulate if necessary to improve the consumer experience of EV charging infrastructure, to ensure the provision at key strategic locations and to require that charging points have "smart" capability [9].

According to the government response on the proposed "Directive" in September 2017, the government will publish National Policy Framework (NPF) to present information on the current quantity, spread and reach of alternative fuels infrastructure across the UK (e.g. EV charging points) and outline the future development of the infrastructure, and how these levels of infrastructure are likely to be achieved. Also, the national legislation imposing certain requirements on infrastructure operators will also be introduced.

B. Grant Schemes for EV Charging Infrastructure

A series of grant schemes have continuously sprung up since 2010. The government set up the plugged-in places (PIPs) scheme in 2010 to match funding for local business and public sector consortia to build their own electric charging points [23]. The scheme ceased the operation in 2013 and its successors are separate installation grants for public sector bodies and local authorities focusing on the workplaces and on-street residential charging points, respectively. Earlier in the same year, the Office for Low Emission Vehicles (OLEV) launched a £13.5 million grant scheme to subsidize householders installing charging equipment at home. In recent years, three grant schemes have been published for the installation of home, workplace and on-street residential charging infrastructure by OLEV, respectively [24].

The EV home-charge scheme (EVHS) provides a grant of up to 75% towards the cost of installing charging points at domestic properties. The workplace charging scheme (WCS) is a voucher-based scheme that provides support for eligible businesses, charities and public sector organizations. For each application, the funding is limited to £300 for each socket up to a maximum of 20 across all sites. The on-street residential charge-point scheme (ORCS) provides grant funding of 75% of the capital costs up to a maximum of £7500 for local authorities.

Specifically, these grant schemes refer to the guidance for consumers or applicants, installers and manufactures. Minimum technical specification for manufacturers of charging point units are particularly pointed out. Authorized installers, approved charge-point models and eligible vehicles are also listed in the schemes.

Furthermore, the government has pledged £80 million to improve the charging infrastructure for EV owners and £30 million to study, design and develop revolutionary vehicle to grid (V2G) technologies [13].

C. Technical Standards of Charging Infrastructure

Apart from some basic standards like British Standard BS 1363-13 (a plugs socket-outlets adaptors and connection units) and British Standard BS EN 60309-2 (plugs, socket-outlets and couplers for industrial purposes) for generally domestic and industrial plug and socket system [25], [26], there are two specific ones for EV charging system in the UK, namely British Standard "EV conductive charging system" (BS EN 61851) and British Standard "plugs, socket-outlets, vehicle connectors and vehicle inlets - conductive charging of EVs" (BS EN 62196). These documents specify the requirements from plugs, socket-outlets, vehicle connectors and vehicle inlets to charging mode and communication.

There are four different types of EV charging system referred to as "modes" [27], [28]. Modes 1-3 are based on alternating current (AC) charging while mode 4 is based on direct current (DC) charging. Modes 1 and 2 use standard wall socket. But in-cable control and protective device (ICCPD) is not incorporated in mode 1. So it is not recommended for charging EV. In contrast, modes 3 and 4 are specialized systems with a dedicated circuit and dedicated socket outlets, both of which have wide range of charging capabilities with mode 3 up to 50 kW and mode 4 up to over 100 kW, respectively. On top of the different types of output power (AC/DC), the charger of mode 4 is built into the charging point itself, while that of mode 3 utilizes the on-board charger of the vehicle, which is another core difference between them.

Tesla has installed bespoke chargers with an adapted type 2 tethered plug that can provide DC energy up to 145 kW across the UK since 2015. This type of charger belongs to DC rapid here.

Three typical categories of charging speed exist in practice [29], [30], i.e., slow, fast and rapid. The charging type, corresponding mode and connector type are summarized in Table II. It is noteworthy that DC power is only used for rapid charging in mode 4 featured as tethered cable on the infrastructure side. For rapid charging, mainly three vehicle-side sockets are utilized by vehicle manufactures. One is type 2 connector (43 kW three-phase output) and the other two are DC connectors called CHAdeMO (usually 50 kW output) and the combined charging system (CCS or Combo 2), respectively. The schematic structure of type 2 is shown in detail in Fig. 2. It has been widely used in both AC and DC charging modes and in both the infrastructure and the vehicles. Two rapid connectors of the latter are simply displayed in Fig. 3. Further information is given in [29].

TABLE II
EV CHARGING SPEED, MODE AND CONNECTOR TYPE

Charging type	Mode	Connector type	
		Infrastructure side	Vehicle side
Slow: 2.4 kW, 3 kW	2	1) BS1363 2) BS EN 60309-2	1) BS EN 62196-2 type 1 (J1772) 2) BS EN 62196-2 type 2
Fast: 3.7 kW, 7.4 kW, 11 kW, 22 kW	3	1) BS EN 62196-2 type2 2) BS EN 62196-2 type 3 3) Tethered lead	1) BS EN 62196-2 type 1 (J1772) 2) BS EN 62196-2 type 2
AC rapid: 43 kW	3	Tethered lead	BS EN 62196-2 type 2
DC rapid: 20-50 kW	4	Tethered lead	1) CHAdeMO 2) Combo 2 (CCS)

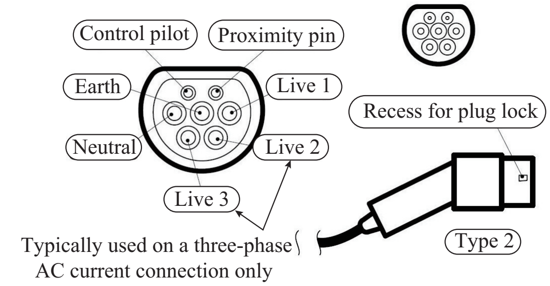

Fig. 2. AC connector type 2.

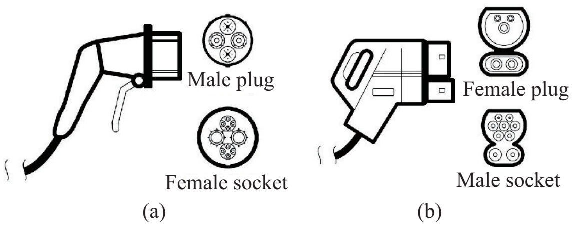

Fig. 3. DC connector. (a) CHAdeMO. (b) Combo 2 or CCS.

As is shown in Fig. 2, the type 2 connector contains seven pins - two small and five larger ones. Two small pins are in the top row and used for signaling. The central one in the middle row is used for earth, while the outer "Live 1" and "Neutral" pins are used for the power supply. The two pins in the bottom row are used for three-phase AC connection. The current of the connector is rated at 63 A per phase for three-phase power supply or 70 A on a single phase.

For manufacturers of EV charging equipment who seek authorization from OLEV, they should apply to OLEV first by filling an application form. Their products would become authorized in the EVHS and WCS if the form provides enough evidence that the equipment is compliant with the corresponding standards set out in the minimum technical specification.

D. Statistics of Public Charging Points

The number of EV charging points has been increasing steadily in recent years from a few hundred in 2011 to 4967 charging locations with 14231 connectors by 2017 [31]. Figure 4 shows the breakdown of charging points or connectors by charger speed, namely "slow" charging units (up to 3 kW), "fast" chargers (7-22 kW), "rapid AC" and "rapid DC" charging units (43-50 kW).

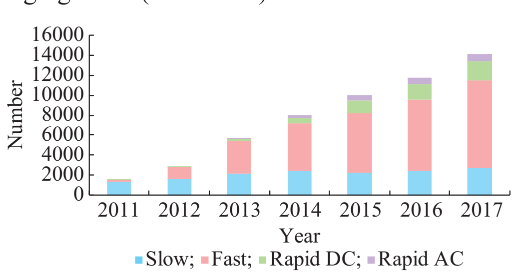

Fig. 4. Charging points by type from 2011 to 2017.

The numbers of rapid charging connectors by type during 2011 and 2016 are shown in Fig. 5. By the end of 2017, the number of rapid connectors has grown over 2600 across CHAdeMO, CCS, Tesla and type 2 rapid chargers from just over 30 CHAdeMO connectors in 2011.

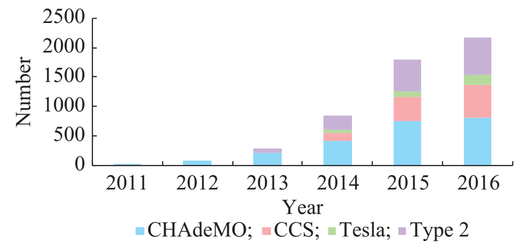

Fig. 5. Rapid charging connectors by type from 2011 to 2016.

The profile of charging points/connectors (by Nov. 2019) in each of the UK regions is shown in Fig. 6. Greater London has the biggest share of charging points followed by the South East England and Scotland, while Northern Ireland and Wales have the least.

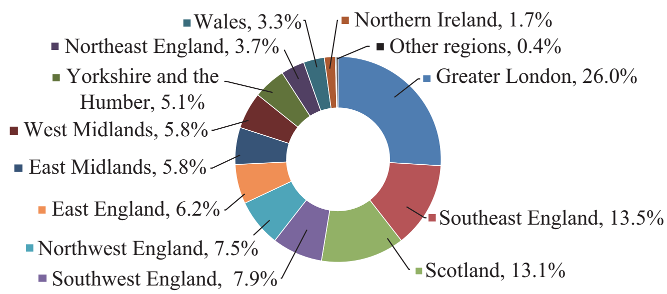

Fig. 6. Profile of charging connectors (total 16464).

In May 2018, it is announced that National Grid has teamed up with Pivot Power to invest £1.6 billion in building grid-scale 50 MW batteries and rapid EV charging docks across the UK [32]. The 2 GW boosted capacity is equivalent to two-thirds of the installed capacity of the long planned Hinkley Point C nuclear power plant but only for a quarter of time with a fraction of the investment.

IV. Design, Location and Cost of EV Charging Infrastructure

In a typical EV charging point project, the following three factors are of the most importance, namely design, location and cost.

A. Design of Charging Points

Charging points are usually floor-mounted or wall-mounted. The main components of such charging point mounted on the floor or on the wall are shown in Fig. 7 and Fig. 8, respectively [33]. It usually consists of four parts, including power supply, communication system, management system and charging system.

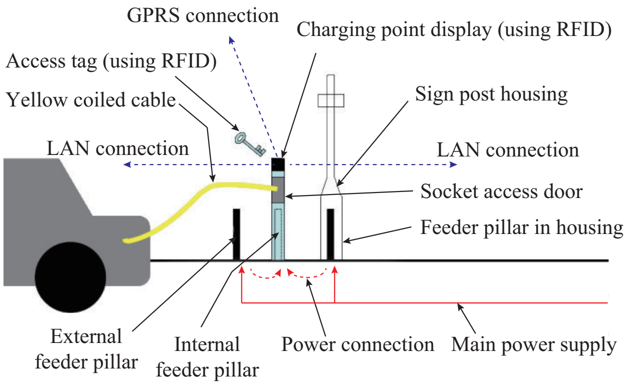

Fig. 7. On-street restricted access charging points (floor-mounted).

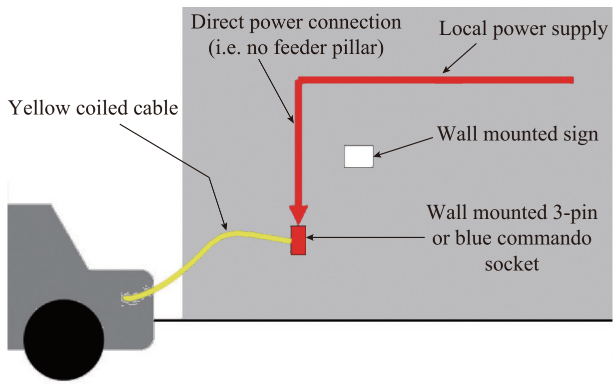

Fig. 8. Off-street open access charging points (wall-mounted).

B. Circuit Topologies of Charging Infrastructure

Globally, several topologies for charging stations are proposed which can be categorized into mainly two most popular types, namely back-to-back AC/DC converters [34]-[36], and transfomerless charging stations [37]-[39]. The back-to-back AC/DC converters consist of a front-end AC/DC converter interfaced with the network via a transformer, whilst the transformerless ones usually decrease the current by connecting the charging station directly to a medium-voltage level. All these topologies could perform bi-directional charging, which could be integrated with battery energy storage system and to provide grid support services. The differences mainly lead towards power density, modularity and reliability. For urban area with limited spaces, a transformerless topology with higher power density may be the better option. For shopping centers and motorway where the infrastructure requires modularity and less control, back-to-back AC/DC converter may be the choice. AC/DC and /DC/DC charging station with high modularity and simpler control would be a suitable choice for charging stations in shopping centers or alongside highways.

From the perspective of charging, it can be further categorized into conductive and inductive charging technologies [40], [41]. For conductive charging, there are mainly five types of converter topologies: power factor corrected (PFC) AC/DC rectifier topologies [42]-[44], isolated DC/DC converter topologies [45], on-board two-stage plug-in EV charger topologies [46], [47], integrated on-board charger topologies, and level 3 off-board charger topologies. Integrated on-board chargers combine the charging stage with the DC/DC converter between the energy storage source and the DC-link of propulsion machine inverter. Therefore, it reduces the component size, weight and cost of the infrastructure [48]-[50]. For fast charging, conventional on-board charger may not be a feasible solution due to cost, size and weight issues. Off-board charging technologies are therefore dominating in this area. Charging unit within a charging station may share the same common AC link or common DC link [51]. Both three-phase AC/DC converters [52], [53] and DC/DC power converters [54], [55] can be adapted. In [56], a modular multilevel converter-based solution for transportation electrification is introduced, where both on-board and off-board charging solutions are presented. The charging topology comparison can be found in Table III. On the other hand, inductive charging mainly relies on inductive power transfer (IPT) technology, which transfers power to load via varying magnetic fields without physical contact. There are mainly two types of IPT, namely transformer-based IPT systems [57] and resonant converter based IPT systems [58], which is the mainstream solution at the moment [59], [60].

TABLE III
CHARGING CIRCUIT TOPOLOGY COMPARISON

Topology	Power supply	DC/DC converter	Advantages	Drawbacks
PFC, rectifier AC/DC [61]	Single-phase or three-phase AC	Isolated, dual active full bridge	Reduced harmonics, robustness, high power factor and high efficiency	High conduction losses
Isolated DC/DC converter [45]	Single-phase or three-phase AC	Resonant/dual active full bridge	Wide output voltage range	Control complexity could be high
Active frontend converter, double compensated DC/DC converter [62]-[64]	Three-phase AC	Buck-boost/LCC resonant/interleaved	Reduced dimension of AC filter, minimized conduction losses, reduced output capacitor ripple	It may require external transformer, and may not be bi-directional
Integrated on-board chargers [48], [49], [65]	Single-phase or three-phase AC	Buck-boost/three-level AC/DC/bridgeless direct AC/DC	Wide input voltage ranges, reduced components, size, weight and cost, one converter for all modes	It may not be bi-directional
Off-board chargers [52]-[55]	Three-phase AC/DC, low to medium voltage level	Phase shifted full bridge/LCC	High efficiency, good power quality, may be directly connected to medium voltage network	It may require isolation transformer

C. Comparison of Charging Point Locations

EVs can be charged using different types of charging points. But due to different locations, different designs need to be adapted. There are mainly four types of charging point locations namely domestic, workplace, public car park and on-street parking.

1) Domestic

More than 60% of UK domestic dwellings have garage or other types of off-street parking [66]. Homeowners are the largest group of motorists in the UK whilst 78% of them have access to off-street parking [67]. Although EV drivers charge at different locations throughout the day, 35% of them charge at home with off-street parking [67], which usually happens between 5 p.m. to 8 p.m.. Residential off-street charging points are usually privately installed and unshared. In domestic environment, charging points are mainly wall-mounted. Due to the fact that most of the residential dwellings in the UK only have single-phase power supply, residential customers will usually have slow (2.4 kW), standard (3 kW) or fast (7 kW) charging points. In typical residential applications, a single-phase power supply with 13 A BS 1363 socket outlet will be used for mode 2 charging. While BS 1363 socket is limited for 13 A, many manufacturers are limiting the maximum charging current to 10 A for mode 2 [30]. Meanwhile, mode 3 usually operates at 3.7 kW (16 A) or 7.4 kW (32 A) with commando sockets or tethered cables. Not all vehicles on the market can make use of the 7.4 kW (32 A) mode 3 system, but it may become increasingly common in the future. Even with slow charging point, it is still considered to be one of the biggest appliances in residential domain. Figure 9 shows the weekly residential charging profile from [68].

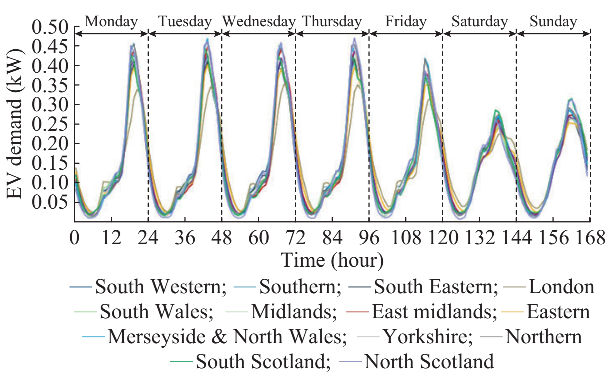

Fig. 9. Weekly demand profile averaged over a whole year at distribution network operator (DNO) licensed area level for residential charging for an average EV.

From the perspective of distribution network operator, it shows a similar evening peak demand across all areas. London is noticeably lower for the evening peak hours possibly due to smaller share of cars used for commuting and lower average commuting distance compared to the rest of the UK. At weekends, the influence from commuters is much lower. If EV uptake becomes norm across the UK and home charging is still dominating, distribution network reinforcement needs to take place to mitigate expected spikes in demand from EV charging.

2) Workplace

Existing EV owners mostly rely on home recharging supported by workplace charging to commute [69]. Companies with parking facilities are often willing to have charging points installed mainly because of their corporate social responsibility (CSR), staff EV scheme, the convenience for visitors or even EV fleet requirements of the company. Furthermore, considering the available government grants and tax benefits, workplace charging points can be installed at a surprisingly low cost, which is therefore very attractive for employers. Workplace sites usually have restricted access to employees and visitors. It is very rare that these charging points will be made accessible to the general public. Meanwhile, unlike home charging, workplace charging has access to three-phase power supply. Therefore, apart from slow and standard charging points, it is common to see fast or even rapid charging points at workplace. A three-phase mode 3 system will usually operate at 11 kW, 22 kW or 43 kW. Since workplace parking usually lasts for several hours, the demand for rapid charging is relatively low. In general, the existing power capacity should be sufficient for some fast charging points. But it may be insufficient for a large number of fast charging points.

With regard to charging behavior, Fig. 10 shows similar results compared to residential charging. London has lower demand for EV charging at workplace, potentially due to space constraints [68]. This is also possibly because the charging points are more commonly used by visitors rather than commuters.

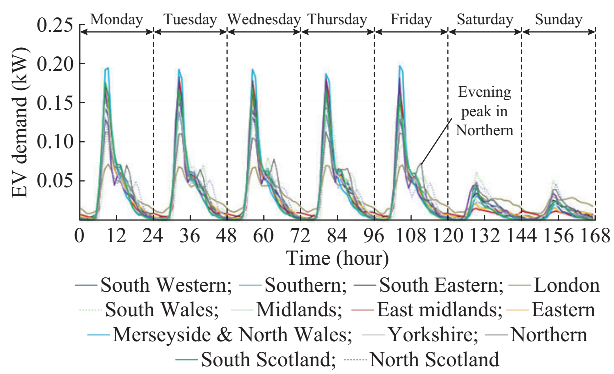

Fig. 10. Weekly demand profile averaged over a whole year at DNO licensed area level for work charging for an average EV.

3) Public Car Park

Home and workplace charging can be further supplemented by the expanding public EV charging network. This includes leisure centers and sports facilities, retail outlets, community facilities, parks and other green spaces, education facilities and motorway services stations. Public car parks are either owned by local councils or private businesses. They are usually enforced and users pay for parking by either pay and display, pay on foot, pay by phone or automatic number plate recognition (ANPR) managed. Most of the public car parks are found in town or city centers for customers or visitors, where parking bays are limited and cost can be at a premium. Signing parking bays to EVs may only need to be justified against the business model and popularity of EVs in the local area. In addition, parking legislation needs to be reviewed to ensure that EV parking spaces are not abused by both non-EV owners and EV owners who park with little charging or completely without charging. Motorists often park at these locations for a limited time depending on their purpose of visit. Therefore, slow or standard charging may not be very helpful for these applications. In commercial applications and public car parks, charging points may operate at higher rates with rapid AC (mode 3) or DC (mode 4) charging to reduce charging times accordingly. Therefore, power supply could be a major challenge to these locations if there is no existing grid connection other than light circuits. In the meantime, charging points can be floor-mounted or wall-mounted in external car parks. On the other hand, they are usually wall-mounted in internal car parks including multi-story ones [33]. The charging points should also be hard-wearing with anti-graffiti coatings.

Comparing the charging behavior for public with residential and workplace, according to Fig. 11, the early morning peak suggests that a large number of these charging points are used by commuters, which may be close to train station or near workplaces. It is likely that these commuters do not have access to off-street parking during night time.

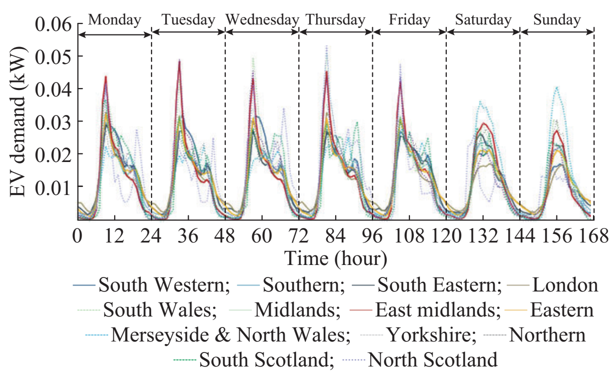

Fig. 11. Weekly demand profile averaged over full year at DNO licensed area level for slow/fast public charging for an average EV.

4) *On-street Parking*

On-street parking locations are usually owned and operated by local or transport authorities. Similar to public car parks, as the sites are usually limited for availability and are often located in town or city centers, parking at these locations will generally be at a premium. Also, the maximum permitted stay for these locations lasts usually 3-4 hours during the day, in which time users would usually expect to achieve at least 80% of the full charging of their vehicles [33]. Hence, rapid AC (mode 3) and DC (mode 4) charging are recommended for these locations. Meanwhile, on-street charging points are usually floor-mounted or footway-mounted. There is usually a high demand for curbside space in busy high streets. It could be difficult to find a suitable location for a charging point that is not currently occupied by a well-utilized parking bay. The space for the infrastructure installation is at a premium because it must be installed at the edge of the footway. Energy supplies may be available from existing feeder pillars nearby. Last but not least, on-street charging points should also be hard-wearing with anti-graffiti coatings.

D. *Installation Cost of Charging Points*

Typical cost of a charging point can be split into three parts: capital cost, installation cost and operation cost. The cost of purchasing and installing charging points can be credited to several factors. The most important factor is whether it is restricted-access or open-access [33]. The restricted-access charging points have significantly higher capital costs and installation costs than open-access points as there are additional costs associated with the purchase and implementation of feeder pillars.

According to [29], [70], the capital cost of an EV charging point is summarized in Table IV.

TABLE IV
CAPITAL COST (EX VAT) OF EV CHARGING POINTS

Type	Cost (£)
Slow/normal (mode 3)	500-1000
Fast type 2 wall mount 7 kW (mode 3)	750-1500
Fast dual type 2 wall mount 7 kW (mode 3)	1700-2700
Fast dual type 2 ground mount 7 kW (mode 3)	1700-5000
Fast dual type 2 wall mount 11 kW or 22 kW (mode 3)	1800-4000
Fast dual type 2 ground mount 11 kW or 22 kW (mode 3)	3000-5000
Rapid dual outlet (mode 3/4)	15000-26000
Rapid triple outlet (mode 3/4)	16000-30000

Installation cost is the most variable in a charging point project. Without detailed information of the site, it is impossible to estimate the installation cost. It is affected by too many factors including but not limited to the charging point model, location and power supply. In practice, the installation could cost as much as the charging point itself [33].

Generally, operation costs include maintenance, servicing, warranties, data services and insurance [29]. Unlike capital cost and installation cost, these are not always covered by government grants. An estimated annual operation cost is summarized in Table V.

TABLE V
OPERATION COST (EX VAT) FOR EV CHARGING POINT

Item	Cost for fast charging (£)	Cost for rapid charging (£)
Annual maintenance inspection	100-200	300-2300
Annual warranty in year 2 or year 3	100-250	500-2600
Annual warranty in year 4 or year 5 and beyond	150-500	700-3000
Annual (continuous) data connection and collection fee	60-200	60-300
Annual insurance for user damage to charging point	500-1000	1000-3000

V. Management and Operation

Charging points can either be operated as a standalone device or connected to a back-end system via network connection. Most of the public car parks need to implement access control and billing function for their charging points. Without a live network connection, standalone charging point will have very limited functionality, especially when the offline user authentication and payment system is involved. Moreover, there is no remote observability over standalone charging points to monitor, diagnose or upgrade the chargers. Therefore, public car park operators would rather prefer connected charging points considering advantages brought by the connectivity over the cost of running such service [30].

A. Management and Supervisory Control System

There are mainly two types of shared charging point operation model, open-access or restricted-access [33]. For open-access charging points, users only need to plug in their vehicle to charge. No further interactions can be made between users and charging points. Therefore, most of charging points are free to charge, yet may incur parking costs. On the contrary, restricted-access charging points usually come with several features, which include user access, user display, remote connection to supplier operation system and local connection to other EV charging points [33]. Users will be provided with radio frequency identification (RFID) or similar technology-based tag or card provided by the charging point supplier to access the charging point. As shown in Fig. 12, it will also contain mobile-network-based communication system, e.g., general packet radio service (GPRS) modem, to communicate with back-end energy charging and user management system. Based on the consumption readings taken from integrated energy metering solution within the charging point, back-end system can bill users based on the usage of electricity. More importantly, with such structure and operation mechanism, it is possible to provide cloud-based smart charging services.

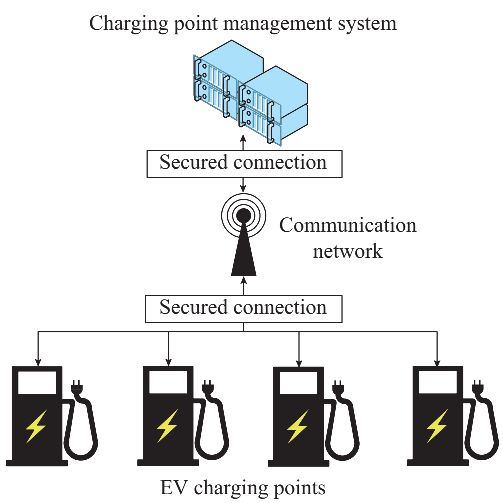

Fig. 12. EV charging point communication schematic.

B. Business Model of Charging Points

At the moment, electricity cost to charge EVs at home are roughly £225 per year based on an estimated annual mileage of 7500, which is equal to £0.03 per mile [71]. In terms of public charging points, the average cost is £0.08 to £0.12 per mile. There are mainly three types of business models for recoupling the cost of energy consumption.

1) Free Charging

For workplace charging, it is common for employer to provide free charging to staffs and visitors. Similarly for public car parks, many of them are often free of charge as well to attract customers to visit their business [72]-[74]. At current stage, compared to publicity, the financial proposition is not very attractive to business owners. They are more than happy to absorb the charging cost. Considering the average hourly cost of £0.70 to the business owner, it is hardly a bank-busting amount while the customers will be shopping in the meantime [75].

2) Subscription

Some charging point network operator runs their scheme on a subscription basis which charges a monthly membership fees with or without additional charges. POLAR Plus, part of POLAR charging network operated by Chargemaster, is one of the biggest charging point network operators in the UK, which has more than 2000 charging points with around 4000 connectors. Members pay £7.85 per month plus additional 10.8 pennies per kWh per charge where applicable. Yet the majority of their charging points are free. It is also introduced as membership fee, connection charges, license fee, etc.

However, the Government has recently proposed the Automated and EVs Bill [9]. It is anticipated to enable government to establish regulations, which allow to require operators to provide standardized measure of accessing public charging points in the near future, ensuring that customers can access any charging points without a specific membership [70].

3) Pay as You Go (PAYG)

PAYG allows charging point owners or network operators to bill EV users based on the energy delivered during charging events via instant or regular payments. It simplifies the EV charging costs for customers. In a survey done in [76], 58% of drivers expressed a preference for PAYG model. As a sustainable business model, it is also endorsed by charging point operators [77]-[79] and OLEV [80]. At the moment, standard charging point charges around £0.20 per kWh while rapid charging costs around £0.30 to £0.40 per kWh, which is in comparison to an average domestic electricity price of £0.14 per kWh [81].

VI. Challenges, Pilot Projects and Future Trends

A. Expansion of Generation, Transmission and Distribution due to Increasing Charging Demand

The growing amount of EVs will drive the total demand and peak demand higher. As a result, the overall reliability of system might be compromised and additional capacity of generation is required. Also, the grid must have the ability to deliver necessary electricity for EV charging even under transmission congestion. Besides, at distribution level where

EVs are particularly prevalent, the grid should accommodate the huge spikes [82] - [86]. Reference [87] presents an EV charging point control methodology to achieve thermal and voltage management of low-voltage (LV) networks. An optimized framework is proposed to effectively control the charging points even with limited information. To cope with high penetration of EVs, the capacity expansion and facility upgrade in existing generation, transmission and distribution parts need to be planned in an integrated way considering both technical and economic benefits. Working with the Welsh Government, Western Power Distribution (WPD) has initiated the superfast electricity project in 2018. It is pioneering in providing three-phase larger capacity service to help the LV network with increased and unbalanced demands from EV charger [88].

B. Faster Charging Technology

Larger EV batteries require faster charging technology to enable long mileage whilst maintaining reasonable charging time. In 2017, several fast charging standardization bodies released new descriptions or protocols to charge EV at up to 200 kW, including China Electricity Council, CHAdeMO and CharIN. Even if some high-power chargers are installed for demonstration in pilot projects, there are no EVs that can charge at the full-rated power yet. CHAdeMO has published their protocol up to 200 kW. A draft protocol CHAdeMO 2.0 allowing charging rate up to 400 kW will be published in 2018 [89]. Similarly, CCS 2.0 and Chinese GB/T 20234.1 are also focusing on 200 kW rated charging standards. Although Tesla' superchargers can only charge up to 120 kW, which is nowhere near 200 kW, they are the only commercially available charging facilities for EVs, which is faster than any other existing technology.

C. Planning of Charging Infrastructures

The availability of convenient charging plays a key role in alleviating range anxiety for long-distance trips and promoting the wide adoption of EVs. Long-term allocation of charging infrastructures within an entire region decides the numbers, sizes and locations of infrastructures to meet the EV charging requirements, which is a complex optimization problem [90] - [92]. The charging demand in the future should be estimated considering the increase of EV numbers and their charging behaviors. Some of the factors, such as the types and models, the cumulative impacts on the grid, the geographic location, and the management of these charging infrastructures, should be paid attention to as well [93].

D. Wireless Charging

Wireless charging system has been widely discussed for high-power applications, especially for stationary EVs. Compared with plug-in system, wireless charging is advantageous in user friendliness, simplicity and reliability. Currently, wireless charging system can be categorized as inductive power transfer, capacitive wireless power transfer, magnetic gear wireless power transfer and resonant inductive power transfer [94] - [98]. Meanwhile, wireless charging in motion has been sought out [99], [100]. However, large air gap and coil misalignment result in low energy efficiency and system reliability. Reference [101] presentes an innovative roadway wireless power transfer system for EVs. In 2019, to boost the "Road to Zero" plan of the UK in improving the infrastructure for EVs, a total of £37 million will be used to transform the network of EV charging points. In particular, it will focus on "pop-up" pavement points and wireless charging [102]. This could be very helpful for those who do not have access to off-street parking.

E. Smart Charging

It is the intelligent charging of EVs, where charging behavior can be shifted based on grid loads, renewable generation and in accordance to the need of EV owners [103] - [106]. EV owners can get monetary benefits offered by the utility if they participate in a program that allows controlled charging or responds to price signal during the periods when curtailment capacity is needed for the grid [107]. The incentive programs, e.g., dynamic prices, should be designed to direct the charging behaviors effectively and economically [108] - [111]. A reliable communication system with a uniform messaging protocol is another challenge, opposed to current large number of proprietary protocols employed by EVs and manufactures of charging equipment. The latest Automated and EV Bill proposed by Department for Transport has set out an ambitious plan of increasing access and availability of charging points for EVs [9]. It points out that all chargers need to be smart in order to provide a robust charging infrastructure to help mitigate energy crisis brought by EV uptake.

Electric Nation, one of the WPD's innovation project, is one of the world's largest trials. It covers more than 40 different makes and models of EVs, providing smart charging services to over 500 EV drivers. In Fig. 13, it can be seen that the annual electricity consumption is to some extent correlated to the battery capacity [112].

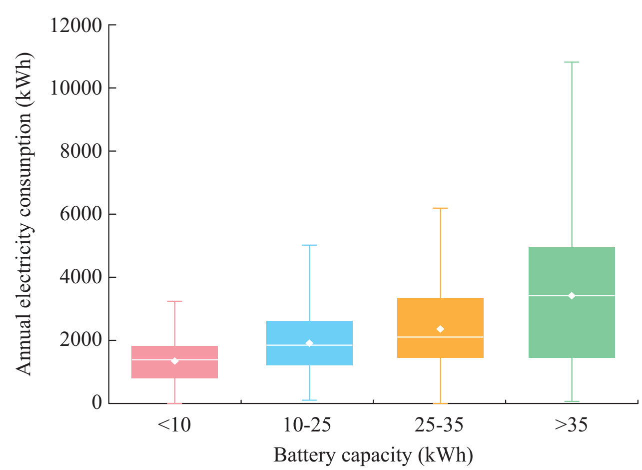

Fig. 13. Annual consumption of charger by battery capacity.

As shown in Fig. 14, there is a great potential in implementing smart charging. Amongst all the valuable project findings, it is suggested that by implementing smart charging, it can mitigate regional network stress and avoid or defer distribution network reinforcement. In the meantime, it also tries to understand the acceptance of customer for this type of demand-side management services.

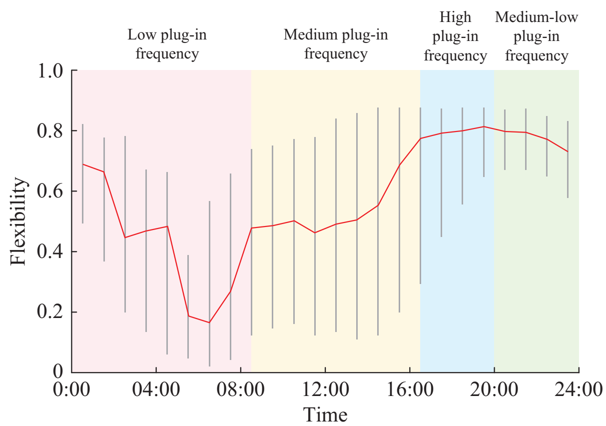

Fig. 14. Flexibility by time of plug-in weekdays (verticle lines indicate range of flexibility).

F. V2G

An EV typically absorbs power from the electrical system, but it can also work as a distributed storage and release power back into the grid, which is known as V2G technology that can bring potential benefits to both EV owners and grid utility [113]-[116]. To further implement V2G, related technologies of facility manufacture, e. g., batteries in EVs and two-way inverters within infrastructures, the business mode for managing EV interaction with the grid, and the construction of smart grid with smart meters, should be put in place first to support the integration of EVs and power grid. It has been long discussed in literature to utilize smart EV charging technology to provide grid ancillary service to improve system stability and reliability [109], [117]-[119].

In July 2017, the UK government launched a £20 million V2G competition, which has been further boosted to £30 million in early 2018 with more than 20 V2G projects involving manufacturers, infrastructure operators, energy suppliers and academia.

VII. Conclusion

This paper introduced the development of EV infrastructures in the UK, including government strategy, standards, design, placement and cost. The successive governments have planned grants and incentives for infrastructure to encourage their growth. In addition, EV infrastructure management and operation have also been discussed to provide an insight towards a sustainable future-proof smart charging network.

The EV uptake in the UK will be substantially increased with the current strategy and roadmap from the government, with a potential projection of 10 million EVs by 2030 [120]. It is anticipated that the development of charging infrastructure is crucial to provide fundamental support to a mass-market. While the government has been heavily investing in the development of battery technologies in recent years, it is not negligible to look into the fast-growing electricity demand from EV across the whole country. Especially in big cities with air pollution congestion, charging takes place where the population density is much higher than anywhere else of the country. Considering the relatively fragile infrastructure of electricity distribution network, the deployment of EV charging infrastructure would require careful long-term planning and improvement in design, not only in locations, but also in converter circuit topology, cost, consumer centric design, reinforcement of electricity distribution network, and social and environmental factors. Apart from improving the energy density of battery technology, the development of EV charging requires strong support in grid development and renewable energy sources integration. Moreover, business models for public EV charging should continue to be exploited and regulated to guarantee a sustainable development in the long term. In the meantime, it is also very important to develop the design, tools and policies to resolve issues related to EV charging for on-street parking.

References

[1] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704-718, Apr. 2007.
[2] A. Y. Saber and G. K. Venayagamoorthy, "Plug-in vehicles and renewable energy sources for cost and emission reductions," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1229-1238, Apr. 2011.
[3] C. Guo and C. C. Chan, "Whole-system thinking, development control, key barriers and promotion mechanism for EV development," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 160-169, Jun. 2015.
[4] International Energy Agency, "Global EV outlook 2018," 2018.
[5] E. I. Department for Business, "2017 UK greenhouse gas emissions, provisional figures," 2018.
[6] HM Government. (2009). Ultra-low carbon vehicles in the UK. [Online]. Available: http://www. dft. gov. uk/adobepdf/187604/ultralowcarbonvehicle.pdf
[7] Office for Low Emission Vehicles. (2013). Driving the future today a strategy for ultra low emission vehicles in the UK. [Online]. Available: https://assets. publishing. service. gov. uk/government/uploads/system/uploads/attachment_data/file/236811/ultra-low-emission-vehicle-strategy-summary.pdf
[8] Office for Low Emission Vehicles, "Investing in ultra low emission vehicles in the UK, 2015 to 2020," 2014.
[9] Department for Transport, "Automated and electric vehicles bill 2017-19," 2017.
[10] Office for Low Emission Vehicles. (2015). Take-up of plug-in car grant continues to rise. [Online]. Available: https://www.gov.uk/government/news/take-up-of-plug-in-car-grant-continues-to-rise
[11] Office for Low Emission Vehicles. (2016). New plug-in car grant levels from March 2016. [Online]. Available: https://assets.publishing.service. gov. uk/government/uploads/system/uploads/attachment_data/file/502056/plug-in-grant-rate-changes-2016.pdf
[12] Office for Low Emission Vehicles. (2016). Low-emission vehicles eligible for a plug-in grant. [Online]. Available: https://www.gov.uk/plug-in-car-van-grants/what-youll-get
[13] Office for Low Emission Vehicles. (2016). Government pledges £290 million boost for low emission vehicles. [Online]. Available: https://www. gov. uk/government/news/government-pledges-290-million-boost-for-low-emission-vehicles
[14] Department for Transport. (2017). 1000 jobs created at new £325 million factory for electric taxis. [Online]. Available: https://www.gov.uk/government/news/1000-jobs-created-at-new-300-million-factory-for-electric-taxis
[15] Office for Low Emission Vehicles, "Tax benefits for ultra low emission vehicles," 2017.
[16] Department for Transport. (2017). Vehicle Licensing Statistics: Annual 2011 to 2017. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699229/ve -hicle-licensing-statistics-2017.pdf

[17] Aurora Energy Research Ltd, "Opportunities in electric vehicle charging at commercial and industrial sites," 2018.

[18] Transport for London, "An ultra low emission vehicle delivery plan for London," 2015.

[19] HM Government. (2011). Carbon plan. [Online]. Available: https://assets. publishing. service. gov. uk/government/uploads/system/uploads/attachment_data/file/47621/1358-the-carbon-plan.pdf

[20] Office for Low Emission Vehicles. (2011). Making the connection. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3986/plug-in-vehicle-infra -structure-strategy.pdf

[21] European Parliament, "Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure," 2014.

[22] Department for Transport, "Consultation on proposed transposition of alternative fuels infrastructure directive government response," 2017.

[23] Office for Low Emission Vehicles. (2013). Lessons learnt from the plugged-in places projects. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/236750/plugged-in-places-lessons-learnt.pdf

[24] Office for Low Emission Vehicles, "Grant schemes for electric vehicle charging infrastructure," 2016.

[25] British Standards Institution, "BS 1363: 13 A plugs, socket-outlets, adaptors and connection units," 2017.

[26] British Standards Institution, "BS EN 60309-2: Plugs, socket-outlets and couplers for industrial purposes," 1999.

[27] British Standards Institution, "BS EN 61851: Electric vehicle conductive charging system," 2014.

[28] British Standards Institution, "BS EN 62196: Plugs, socket-outlets, vehicle connectors and vehicle inlets - conductive charging of electric vehicles," 2017.

[29] UK Electric Vehicle Supply Equipment Association, "General procurement guidance for electric vehicle charge points," 2015.

[30] British Electrotechnical and Allied Manufacturers Association, "A guide to electric vehicle infrastructure," 2015.

[31] Zap Map. (2018). Charging point statistics 2018. [Online]. Available: https://www.zap-map.com/statistics/

[32] J. Murray. (2018). World's largest battery and car-charging network planned for UK. [Online]. Available: https://www.telegraph.co.uk/business/2018/05/21/worlds-largest-battery-car-charging-network-planned-uk/

[33] Transport for London, "Guidance for implementation of electric vehicle charging infrastructure," 2010.

[34] S. Rivera, B. Wu, S. Kouro *et al.*, "Electric vehicle charging station using a neutral point clamped converter with bipolar DC bus," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 1999-2009, Aug. 2015.

[35] B. Sun, T. Dragičević, F. D. Freijedo *et al.*, "A control algorithm for electric vehicle fast charging stations equipped with flywheel energy storage systems," *IEEE Transactions on Power Electronics*, vol. 31, no. 9, pp. 6674-6685, Jan. 2016.

[36] S. Rivera and B. Wu, "Electric vehicle charging station with an energy storage stage for split-DC bus voltage balancing," *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2376-2386, Jan. 2017.

[37] R. Crosier and S. Wang, "*dq*-frame modeling of an active power filter integrated with a grid-connected, multifunctional electric vehicle charging station," *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5702-5716, Feb. 2013.

[38] M. Vasiladiotis and A. Rufer, "A modular multiport power electronic transformer with integrated split battery energy storage for versatile ultrafast EV charging stations," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 5, pp. 3213-3222, Nov. 2015.

[39] G. Waltrich, J. L. Duarte, and M. A. M. Hendrix, "Multiport converter for fast charging of electrical vehicle battery," *IEEE Transactions on Industrial Applications*, vol. 48, no. 6, pp. 2129-2139, Oct. 2012.

[40] A. Khaligh and S. Dusmez, "Comprehensive topological analysis of conductive and inductive charging solutions for plug-in electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3475-3489, Aug. 2012.

[41] L. Rubino, C. Capasso, and O. Veneri, "Review on plug-in electric vehicle charging architectures integrated with distributed energy sources for sustainable mobility," *Applied Energy*, vol. 207, pp. 438-464, Dec. 2017.

[42] F. Musavi, W. Eberle, and W. G. Dunford, "A high-performance single-phase bridgeless interleaved PFC converter for plug-in hybrid electric vehicle battery chargers," *IEEE Transactions on Industrial Applications*, vol. 47, no. 4, pp. 1833-1843, May 2011.

[43] F. Musavi, W. Eberle, and W. G. Dunford, "A phase shifted semi-bridgeless boost power factor corrected converter for plug in hybrid electric vehicle battery chargers," in *Proceedings of 2011 26th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, USA, Mar. 2011, pp. 821-828.

[44] B. Singh, B. N. Singh, A. Chandra *et al.*, "A review of single-phase improved power quality AC-DC converters," *IEEE Transactions on Industrial Electronics*, vol. 50, no. 5, pp. 962-981, Oct. 2003.

[45] D. Aggeler, F. Canales, H. Z. De La Parra *et al.*, "Ultra-fast DC-charge infrastructures for EV-mobility and future smart grids," in *Proceedings of 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenberg, Sweden, Oct. 2010, pp. 1-8.

[46] H. Chae, H. Moon, and J. Lee, "On-board battery charger for PHEV without high-voltage electrolytic capacitor," *Electronics Letters*, vol. 46, no. 25, pp. 1691-1692, Dec. 2010.

[47] H. J. Chae, W. Y. Kim, S. Y. Yun *et al.*, "3.3 kW on board charger for electric vehicle," in *Proceedings of 8th International Conference on Power Electronics - ECCE Asia*, Jeju, South Korea, May-Jun. 2011, pp. 2717-2719.

[48] Y. Lee, A. Khaligh, and A. Emadi, "Advanced integrated bidirectional AC/DC and DC/DC converter for plug-in hybrid electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 3970-3980, Jul. 2009.

[49] D. C. Erb, O. C. Onar, and A. Khaligh, "An integrated bi-directional power electronic converter with multi-level AC-DC/DC-AC converter and non-inverted buck-boost converter for PHEVs with minimal grid level disruptions," in *Proceedings of 2010 IEEE Vehicle Power and Propulsion Conference*, Lille, France, Sept. 2010, pp. 1-6.

[50] G. Pellegrino, E. Armando, and P. Guglielmi, "An integral battery charger with power factor correction for electric scooter," *IEEE Transactions on Power Electronics*, vol. 25, no. 3, pp. 751-759, Sept. 2010.

[51] S. Bai and S. Lukic, "Design considerations for DC charging station for plug-in vehicles," in *Proceedings of 2011 IEEE Vehicle Power and Propulsion Conference*, Lille, France, Sept. 2011, pp. 1-6.

[52] A. Arancibia, K. Strunz, and F. Mancilla-David, "A unified single- and three-phase control for grid connected electric vehicles," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 1780-1790, Sept. 2013.

[53] N. B. H. Youssef, K. Al-Haddad, and H. Y. Kanaan, "Implementation of a new linear control technique based on experimentally validated small-signal model of three-phase three-level boost-type Vienna rectifier," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1666-1676, Apr. 2008.

[54] K. Jin, X. Ruan, M. Yang *et al.*, "A hybrid fuel cell power system," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 4, pp. 1212-1222, Nov. 2009.

[55] R. Beiranvand, B. Rashidian, M. R. Zolghadri *et al.*, "Designing an adjustable wide range regulated current source," *IEEE Transactions on Power Electronics*, vol. 25, no. 1, pp. 197-208, Aug. 2010.

[56] D. Ronanki and S. S. Williamson, "Modular multilevel converters for transportation electrification: challenges and opportunities," *IEEE Transactions on Transportation Electrification*, vol. 4, no. 2, pp. 399-407, Jan. 2018.

[57] H. Ayano, K. Yamamoto, N. Hino *et al.*, "Highly efficient contactless electrical energy transmission system," in *Proceedings of IEEE 2002 28th Annual Conference of the Industrial Electronics Society - IECON 02*, Sevilla, Spain, Nov. 2002, pp. 1364-1369.

[58] C. S. Wang, O. H. Stielau, and G. A. Covic, "Design considerations for a contactless electric vehicle battery charger," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 5, pp. 1308-1314, Sept. 2005.

[59] Z. Bi, T. Kan, C. C. Mi *et al.*, "A review of wireless power transfer for electric vehicles: prospects to enhance sustainable mobility," *Applied Energy*, vol. 179, pp. 413-425, Oct. 2016.

[60] R. Bosshard and J. W. Kolar, "Inductive power transfer for electric vehicle charging: technical challenges and tradeoffs," *IEEE Power Electronics Magazine*, vol. 3, no. 3, pp. 22-30, Sept. 2016.

[61] D. S. Gautam, F. Musavi, M. Edington *et al.*, "An automotive onboard 3.3 kW battery charger for PHEV application," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3466-3474, Jul. 2012.

[62] S. Jaganathan and W. Gao, "Battery charging power electronics converter and control for plug-in hybrid electric vehicle," in *Proceedings of 2009 IEEE Vehicle Power and Propulsion Conference*, Dearborn, USA, Sept. 2009, pp. 440-447.

[63] J. S. Kim, G. Y. Choe, H. M. Jung *et al.*, "Design and implementation of a high-efficiency on-board battery charger for electric vehicles with frequency control strategy," in *Proceedings of 2010 IEEE Vehicle Power and Propulsion Conference*, Lille, France, Sept. 2010, pp. 1-6.

[64] J. Lai, L. Zhang, Z. Zahid *et al*., "A high-efficiency 3.3 kW bidirectional on-board charger," in *Proceedings of 2015 IEEE 2nd International Future Energy Electronics Conference (IFEEC)*, Taipei, China, Nov. 2015, pp. 1-5.
[65] H. Chen, X. Wang, and A. Khaligh, "A single stage integrated bidirectional AC/DC and DC/DC converter for plug-in hybrid electric vehicles," in *Proceedings of 2011 IEEE Vehicle Power and Propulsion Conference*, Chicago, USA, Sept. 2011, pp. 1-6.
[66] RAC Foundation, "Spaced out perspectives on parking policy," 2012.
[67] PWC, "Charging ahead! The need to upscale UK electric vehicle charging infrastructure," 2018.
[68] Elementenergy, "EV charging behaviour study final report," 2019.
[69] Office for Low Emission Vehicles, "Uptake of ultra low emission vehicles in the UK," 2015.
[70] Energy Saving Trust, "Guide to chargepoint infrastructure for business users," 2017.
[71] RGP, "Electric vehicle charging points: a summary guide for developers," 2016.
[72] Pod-Point. (2019). Lidl Rapid Charging Stations. [Online]. Available: https://pod-point.com/landing-pages/lidl-rapid-charging-stations
[73] Ecotricity. (2013). IKEA installs EV chargers at all of its UK stores. [Online]. Available: https://www. ecotricity. co. uk/news/news-archive/2013/ikea-installs-ev-chargers-at-all-of-its-uk-stores
[74] What Car. (2009). Electric car charging at Sainsbury's. [Online]. Available: https://www. whatcar. com/news/electric-car-charging-sainsburys/
[75] D. Pratt. (2018). Long read: driving change - how the UK is ready and waiting for the electric future of transport. [Online]. Available: https://www. current-news. co. uk/blogs/long-read-driving-change-how-the-uk-is-ready-and-waiting-for-the-electric-f
[76] Energy Saving Trust, "A feasibility study into a rapid chargepoint network for plug-in taxis," 2016.
[77] Zero Carbon World. (2019). ZeroNet: simple, reliable charging. [Online]. Available: http://zerocarbonworld.org/zero-net
[78] ESB EV Solutions, "No connection or set up fees - just charge and go," 2019.
[79] Charge Your Car. (2013). Charge Your Car launches app. [Online]. Available: http://www. chargeyourcar. org. uk/news/charge-your-car-launches-app/
[80] Office for Low Emission Vehicles, "Grants to provide residential on-street and rapid chargepoints for plug-in vehicles: guidance for local authorities," 2013.
[81] Zap Map. (2019). EV rapid charge cost comparison. [Online]. Available: https://www.zap-map.com/ev-rapid-charge-cost-comparison/
[82] L. P. Fernandez, T. G. S. Roman, R. Cossent *et al*., "Assessment of the impact of plug-in electric vehicles on distribution networks," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 206-213, May 2011.
[83] M. Z. Fortes, D. F. Silva, T. P. Abud *et al*., "Impact analysis of plug-in electric vehicle connected in real distribution network," *IEEE Latin America Transactions*, vol. 14, no. 5, pp. 2239-2245, Aug. 2016.
[84] J. M. Sexauer, K. D. McBee, and K. A. Bloch, "Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 847-854, Oct. 2013.
[85] H. Liu, P. Zeng, J. Guo *et al*., "An optimization strategy of controlled electric vehicle charging considering demand side response and regional wind and photovoltaic," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 232-239, Jun. 2015.
[86] J. Zhu, W. Gu, P. Jiang *et al*., "Integrated approach for optimal island partition and power dispatch," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 3, pp. 449-462, May 2018.
[87] J. Quirós-Tortós, L. F. Ochoa, S. W. Alnaser *et al*., "Control of EV charging points for thermal and voltage management of LV networks," *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 3028-3039, Sept. 2016.
[88] Western Power Distribution, "Western power distribution electric vehicle strategy," 2019.
[89] CHAdeMO, "2017 activity report," 2018.
[90] S. Wang, Z. Y. Dong, F. Luo *et al*., "Stochastic collaborative planning of electric vehicle charging stations and power distribution system," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 1, pp. 321-331, Feb. 2018.
[91] A. Foley and B. O. Gallachoir, "Analysis of electric vehicle charging using the traditional generation expansion planning analysis tool WASP-IV," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 240-248, Jun. 2015.
[92] Y. Xiang, Z. Liu, J. Liu *et al*., "Integrated traffic-power simulation framework for electric vehicle charging stations based on cellular automaton," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 4, pp. 816-820, Jul. 2018.
[93] A. Y. S. Lam, Y. Leung, and X. Chu, "Electric vehicle charging station placement: formulation, complexity, and solutions," *IEEE Transactions on Smart Grid*, vol. 5, no. 6, pp. 2846-2856, Aug. 2014.
[94] K. A. Kalwar, M. Aamir, and S. Mekhilef, "Inductively coupled power transfer (ICPT) for electric vehicle charging - a review," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 462-475, Jul. 2015.
[95] D. Leskarac, C. Panchal, S. Stegen *et al*., "PEV charging technologies and V2G on distributed systems and utility interfaces," in *Vehicle-to-Grid: Linking Electric Vehicles to the Smart Grid*, J. Hossain and J. Lu, Ed. London: Institution of Engineering and Technology, 2015, pp. 157-221.
[96] S. Y. R. Hui, W. Zhong, and C. K. Lee, "A critical review of recent progress in mid-range wireless power transfer," *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4500-4511, Mar. 2014
[97] S. Li and C. C. Mi, "Wireless power transfer for electric vehicle applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 1, pp. 4-17, Apr. 2015.
[98] T. N. Gücin, M. Biberoğlu, and B. Fincan, "Constant frequency operation of parallel resonant converter for constant-current constant-voltage battery charger applications," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 1, pp. 186-199, Jan. 2019.
[99] S. Lukic and Z. Pantic, "Cutting the cord: Static and dynamic inductive wireless charging of electric vehicles," *IEEE Electrification Magazine*, vol. 1, no. 1, pp. 57-64, Oct. 2013.
[100] F. P. Deflorio, L. Castello, I. Pinna *et al*., "'Charge while driving' for electric vehicles: road traffic modeling and energy assessment," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 277-288, Jun. 2015.
[101] C. C. Mi, G. Buja, S. Y. Choi *et al*., "Modern advances in wireless power transfer systems for roadway powered electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 10, pp. 6533-6545, Jun. 2016.
[102] Department for Transport, "Solar, high speed and wifi charging set to revolutionise electric transport," 2019.
[103] K. S. Reddy, L. K. Panwar, R. Kumar *et al*., "Distributed resource scheduling in smart grid with electric vehicle deployment using fireworks algorithm," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 2, pp. 188-199, Apr. 2016.
[104] P. Liu and J. Yu, "Identification of charging behavior characteristic for large-scale heterogeneous electric vehicle fleet," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 3, pp. 567-581, May 2018.
[105] Z. M. Haider, K. K. Mehmood, M. K. Rafique *et al*., "Water-filling algorithm based approach for management of responsive residential loads," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 1, pp. 118-131, Jan. 2018.
[106] A. S. T. Tan, D. Ishak, R. Mohd-Mokhtar *et al*., "Predictive control of plug-in electric vehicle chargers with photovoltaic integration," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 6, pp. 1264-1276, Nov. 2018.
[107] M. Wang, Y. Mu, T. Jiang *et al.*, "Load curve smoothing strategy based on unified state model of different demand side resources," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 3, pp. 540-554, May 2018.
[108] J. F. Franco, M. J. Rider, and R. Romero, "A mixed-integer linear programming model for the electric vehicle charging coordination problem in unbalanced electrical distribution systems," *IEEE Transactions on Smart Grid*, vol. 6, no. 5, pp. 2200-2210, Feb. 2015.
[109] J. Hu, S. You, M. Lind *et al.*, "Coordinated charging of electric vehicles for congestion prevention in the distribution grid," *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 703-711, Nov. 2014.
[110] L. Hua, J. Wang, and C. Zhou, "Adaptive electric vehicle charging coordination on distribution network," *IEEE Transactions on Smart Grid*, vol. 5, no. 6, pp. 2666-2675, Jul. 2014.
[111] J. Meng, Y. Mu, J. Wu *et al.*, "Dynamic frequency response from electric vehicles in the Great Britain power system," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 203-211, Jun. 2015.
[112] Western Power Distribution. (2019). Electric nation. [Online]. Available: http://www.electricnation.org.uk
[113] C. Liu, K. T. Chau, D. Wu *et al.*, "Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies," *Proceedings of the IEEE*, vol. 101, no. 11, pp. 2409-2427, Jul. 2013.

[114] J. Cai, C. Chen, P. Liu *et al.*, "Centralized control of parallel connected power conditioning system in electric vehicle charge - discharge and storage integration station," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 269-276, Jun. 2015.
[115] M. Kiaee, A. Cruden, and S. Sharkh, "Estimation of cost savings from participation of electric vehicles in vehicle to grid (V2G) schemes," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 249-258, Jun. 2015.
[116] N. Erdogan, F. Erden, and M. Kisacikoglu, "A fast and efficient coordinated vehicle-to-grid discharging control scheme for peak shaving in power distribution system," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 3, pp. 555-566, May 2018.
[117] S. Debbarma and A. Dutta, "Utilizing electric vehicles for LFC in restructured power systems using fractional order controller," *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 2554-2564, Mar. 2017.
[118] K. Knezović, S. Martinenas, P. B. Andersen *et al.*, "Enhancing the role of electric vehicles in the power grid: field validation of multiple ancillary services," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 1, pp. 201-209, Oct. 2017.
[119] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle-to-grid energy and ancillary services," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 351-359, Sept. 2012.
[120] SP Energy Networks, "Review of electric vehicle uptake forecasts," 2016.

Tianjin Chen received the M.Sc. degree in power electronics and power transmission from Huazhong University of Science and Technology, Wuhan, China in 2000. He is currently working as the Chief Engineer of XU JI Power Co., Ltd., Xuchang, China. His research interests are power conversion technology, FACTS technology, energy storage technology, and electric vehicle charging technology.

Xiao-Ping Zhang received the B. Eng., M. Sc. and Ph. D. degrees from Southeast University, Nanjing, China in 1988, 1990, 1993, respectively, all in electrical engineering. He was an Associate Professor with the University of Warwick, Coventry, UK. He was with the China State Grid EPRI (NARI Group) on EMS/DMS advanced application software research and development from 1993 to 1998. From 1998 to 1999, he was visiting University of Manchester Institute of Science and Technology (UMIST), Manchester, UK. From 1999 to 2000, he was an Alexander-von-Humboldt Research Fellow with the University of Dortmund, Dortmund, Germany. He is currently a Professor of electrical power systems with the University of Birmingham, Birmingham, UK, and he is also the Director of Smart Grid, Birmingham Energy Institute and the Co-Director of the Birmingham Energy Storage Center. He has co-authored the first and second edition of the monograph "Flexible AC Transmission Systems: Modeling and Control", published by Springer in 2006, and 2012. He has co-authored the book "Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models", published by IEEE Press/Wiley in 2010. He is a Fellow of the IEEE, a Foreign Fellow of Chinese Society for Electrical Engineering, and a Fellow of the IET. His research interests include smart grid, HVDC & FACTS, operation and planning of power grids, renewable energy integration and stability control, energy system modeling and energy economics, and cyber-physical system modeling.

Jianji Wang graduated from Shandong Electric Power College in 2008, and is currently working in Linyi Power Supply Company under State Grid Shandong Electric Power Company, Linyi, China. His research interests include construction and operation of charging facilities.

Jianing Li received the B.Eng. degree in electrical and electronic engineering from Huazhong University of Science and Technology, Wuhan, China in 2011. He then received the Ph.D. degree in electrical and electronic engineering from the University of Birmingham, Birmingham, UK in 2016. He is currently a Lecturer in the Department of Electronic, Electrical and Systems Engineering with the University of Birmingham. His research interests include distributed energy resource, energy storage systems, EV, energy management system and smart grid technology.

Cong Wu received the B.Eng. and M.Sc. degrees in electrical engineering from China Agricultural University, Beijing, China, in 2015 and 2017, respectively. He has been pursuing the Ph.D. degree in the Department of Electronic, Electrical and Systems Engineering, University of Birmingham, Birmingham, UK since 2018. His research interests include renewable energy and electricity market.

Mingzhu Hu received the B.Eng. degree from Harbin University of Science and Technology, Harbin, China in 1999, and is currently working as the Director of the Scientific Research Management Department of XU JI Power Supply Co., Ltd., Xuchang, China.

Huiping Bian received B.Eng. degree from Xuchang University, Xuchnag, China in 2009, and is currently engaged in the scientific research management in XU JI Power Supply Co., Ltd., Xuchang, China.