Postprint of article in *Transportation research Part D: Transport and Environment, Volume* 62, 508 - 523. doi:10.1016/j.trd.2018.04.002

Hardman, S.; Jenn, A.; Tal, G.; Axsen, J.; Beard, G.; Daina, N.; Figenbaum, E.; Jakobsson, N.; Jochem, P. E. P.; Kinnear, N. A. D.; Plötz, P.; Pontes, J. P.; Refa, N.; Sprei, F.; Turrentine, T. S.; Witkamp, B. (2018).

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Transportation research Part D: Transport and Environment, Volume 62, 508 - 523.
doi:10.1016/j.trd.2018.04.002

Postprint of article in *Transportation research Part D: Transport and Environment, Volume* 62, 508 - 523. doi:10.1016/j.trd.2018.04.002

A review of consumer preferences of and interactions with electric vehicle charging infrastructure

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Abstract

This paper presents a literature review of studies that investigate infrastructure needs to support the market introduction of plug-in electric vehicles (PEVs). It focuses on literature relating to consumer preferences for charging infrastructure, and how consumers interact with and use this infrastructure. This includes studies that use questionnaire surveys, interviews, modelling, GPS data from vehicles, and data from electric vehicle charging equipment. These studies indicate that the most important location for PEV charging is at home, followed by work, and then public locations. Studies have found that more effort is needed to ensure consumers have easy access to PEV charging and that charging at home, work, or public locations should not be free of cost. Research indicates that PEV charging will not impact electricity grids on the short term, however charging may need to be managed when the vehicles are deployed in greater numbers. In some areas of study the literature is not sufficiently mature to draw any conclusions from. More research is especially needed to determine how much infrastructure is needed to support the roll out of PEVs. This paper ends with policy implications and suggests avenues of future research.

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Postprint of article in *Transportation research Part D: Transport and Environment, Volume* 62, 508 - 523. doi:10.1016/j.trd.2018.04.002

1. Introduction

Plug-in electric vehicles (PEVs), which include both battery electric vehicles (BEVs) and plug in hybrid electric vehicles (PHEVs), are more efficient and less polluting than the majority of internal combustion engine vehicles (ICEVs) (Jochem et al., 2015a; Nordelöf et al., 2014; Offer et al., 2011; Plötz et al., 2017a; Poullikkas, 2015). They will need to increase market shares to have an impact on urban air pollution, energy consumption, and climate change. The success of PEV technology is partially reliant on the development of recharging infrastructure, among other constraints (Wolinetz and Axsen, 2017). There are currently only a small number of studies published in the academic literature that review existing research on the development of PEV recharging infrastructure (Broadbent et al., 2017; Hall and Lutsey, 2017). This paper builds on these studies to provide more insights to policymakers and academics.

Whilst PEVs can be recharged from standard plug sockets, these sockets charge PEVs slowly and are not always easily accessible by vehicles. Developing dedicated infrastructure can encourage more consumers to purchase PEVs and allow them to drive more electric miles (Adepetu et al., 2016; Ajanovic and Haas, 2016; Bonges and Lusk, 2016; Caperello et al., 2015; Egbue and Long, 2012; Graham-Rowe et al., 2012; Javid and Nejat, 2017; Mersky et al., 2016; Ozaki and Sevastyanova, 2011; Plötz et al., 2016; Zhang et al., 2016; Zheng et al., 2012). The development of this infrastructure needs to be carefully considered so that the benefits of infrastructure development can be maximised. PEV charging infrastructure development can be driven by policymakers, OEMs, utilities, workplaces, housing developers, charging infrastructure companies, municipalities, parking companies, shopping centres, fuel stations, and any other stakeholders. Infrastructure needs to be developed to fit the needs and use patterns of consumers whilst also considering the impact of PEVs on local and regional electricity grids. Policymakers have some ability in ensuring the correct infrastructure is set up and can regulate how infrastructure is deployed. There are currently few studies published in the academic literature that review existing research to provide information on the considerations for the development of PEV recharging infrastructure for consumers. This paper reviews literature on consumer interactions with electric vehicle charging infrastructure and literature on consumer preferences for infrastructure. This includes investigating the impact of when consumers use infrastructure on electricity grids and how this can be managed. This papers' contribution to the literature is an improved understanding of how infrastructure for PEVs can be developed such that it encourages consumers to purchase and use PEVs, whilst also considering how to manage charging of PEVs to avoid negative impacts to the power grid.

This review considers charging for light duty BEVs and PHEVs which can have very different charging requirements. BEVs are powered only by a large battery pack (17–100 kWh). These vehicles typically have a driving range of between 70 and 120 miles, with some vehicles now having ranges of 200–300 miles. Once the battery in a BEV is depleted the vehicle needs to be recharged from a charge point or electricity outlet. PHEVs have a smaller battery pack (4-17kWh) and an internal combustion engine (ICE), they usually have an electric driving range of between 10 and 50 miles. Once a PHEV battery is depleted the vehicle can continue driving with the use of its ICE. The battery can be recharged from a charge point or electricity outlet. The ICE can also charge the battery or can be used to maintain the level of charge in the pack. Due to the differences between PHEVs and BEVs, the vehicles are driven and charged differently by consumers. BEVs with lower driving ranges generally have lower vehicle miles travelled (VMT) that ICEVs on average, whereas PHEVs tend to have similar VMT. BEVs with longer driving ranges (e.g. Tesla BEVs) also have similar VMT as typical ICEVs (Nicholas et al., 2017b; Tal et al., 2013).

Next, we provide background information on charging modes and levels and then introduce the approach to the literature review. Section 2 then summarises the literature, whilst Section 3 concludes with insights for policymakers and literature gaps.

1.1. Introduction to charging modes and levels

This paper considers the importance of charging infrastructure for light-duty passenger vehicles. In this section, we further explain the different modes and levels of charging for these vehicles, which is current as of the writing of this paper.

The charge time of a PEV depends primarily on the charge level of the battery. Second, it depends on the technology in the car (limited by ability of the battery to accept a high charge rate), the charging cable used, and the charging station (Electric Vehicle Supply Equipment, EVSE). The international standard IEC 61851 classifies four different charging modes (IEC, 2003) (Table 1). The slowest charge is mode 1, which uses no control for communication and consequently does not consider load quality, which can lead to grid overload. Mode 2 charging is controlled via a control box in the charge cable. This communicates with the car and can contribute towards grid stability. Both mode 1 and 2 use a domestic plug outlet and a vehicle specific plug (mainly Type 2 (IEC 62196) or Type 1 (SAE J1772)) as inlet to the vehicle. These mostly allow a charging power up to about 1.5–3 kW (110–220 V). Mode 3 charging simplifies the communication between the grid and the car as the cable is capable of transferring information (e.g. IEC 15118). Currently mode 3 home and public charging stations use either Type 2 or Type 1 outlets. This allows the EVSE to identify the car and to optimally schedule the charging process from the grid perspective as well as offering additional services such as preconditioning (Ensslen et al., 2016). Finally, mode 4 charging provides DC (direct current) fast charging. Here, the cable is connected to the charging station. In Europe CHAdeMO ((JEVS) G105-1993) is the dominant charge point connector, though Europe and China are now shifting to the Combined Charging System (CCS) standard, which uses the Type 2 and an additional DC connector on the plug. In the European Union CCS connectors are the standard charge point type and must be installed at all charge point locations due to an EU directive. Additional connectors, for example CHAdeMO and Tesla connectors, can also be installed in addition to CCS. CCS allows charging rates of up to 40 kW, though current charge rates are 40–150 kW. These chargers are typically installed in locations where consumers need to recharge their PEV quickly, such as on travel corridors (Jochem et al., 2015b).

Tabel 1
Different modes of charging (and the associated levels in North America), the power associated with these levels, typical locations and the time to charge 100 miles of range.

Mode [IEC 61851]	Power [kW]	Possibility to control charging	Typical location	Socket system [Outlet|Inlet]	Time to charge 100 miles
Mode 1 (Level 1)	1–3	No	Home	Domestic plug|Type 1/2	>10 h
Mode 2 (Level 2)	1–7	Yes	Home, Work	Domestic plug|Type 1/2	2–12 h
Mode 3 (Level 3)	Up to 43.5	Yes	Work, Public	Type 1/2|Type 1/2	0.5–1.5 h
Mode 4 (Level 4)	Currently 50–150 (< 4 0 0)	Yes	Corridor	CCS (CHAdeMO)	<15 min

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In North America chargers are classified depending on the charge level. The slowest charge is from level 1 chargers. Using standard plug sockets these charge PEVs with 100 miles of range in around 24 h and are mostly used for overnight charging at home. Level 2 (208–240 V) charging has a wide range of charging speeds based on the charging equipment used and the vehicle capability. Level 2 infrastructure can charge a PEV with 100 miles of range in 4–12 h. Dedicated charge points are typically needed for level 2 chargers in USA. In Europe, Australia, most of Asia, and most of South America, level 2 charging is the standard level from domestic plug sockets. Level 2 chargers are often installed at homes, workplaces, and in public locations. DC fast chargers charge PEVs in the fastest possible time. They are also considerably more expensive than level 2 chargers (sometimes ten times more) (Idaho National Laboratory, 2015). They have very high power demands, due to the high kW power outputs of the charge points.

1.2. Research approach

This study concentrates on topics relevant to the development of PEV recharging for consumers. The aim is understanding how infrastructure could be developed to ensure the successful market introduction of PEVs based on how consumers use PEV infrastructure, that is, among current users and potential future users. The review focuses less on issues associated with PEV grid integration or technical aspects associated with PEV recharging. The topics in this review were determined by the authors of the paper as being topics relevant to PEV charging infrastructure and consumers. The five topics in this paper emerged as important to this area of research in two workshops with the authors of this paper in June 2017 and another in October 2017. These topics were identified as ones that need to be addressed to achieve a smooth roll out of PEVs and are all areas where academic literature currently exists. Five topics were identified; search terms were used to find literature relevant to the topics by the title of the study. Once these studies were identified their abstracts were screened to ensure they were relevant to the review. Irrelevant studies were not included in the review based on their lack of fit with the topics of interest. Relevant studies were reviewed and their key findings extracted for use in this paper. The papers reviewed included ones that use questionnaire surveys, interviews, GPS data from ICEVs and PEVs, data from on-board vehicle loggers, and data from electric vehicle supply equipment (EVSE), and from studies that construct models based on national or regional travel surveys (e.g. California Household Travel Survey).

2. Literature review

2.1. Introduction to literature topics and methods used

In the following sections studies on charge point location, charge point access and payment, cost to charge, the required number of charging stations including considerations for households without off street parking, and when charging occurs and how to manage this are reviewed. Table 2 shows the authors, year of publication, location of study, methods used, and key findings of the reviewed studies. The table shows whether studies investigate BEVs, PHEVs, or whether they consider both types of PEVs (PHEVs and BEVs). Most studies consider both PHEVs and BEVs, with some only considering BEVs or PHEVs. Some studies investigate PEVs in general, without distinguishing between BEVs and PHEVs.

Some of the earliest papers in this review use data from general travel surveys, for example the US National Household Travel Survey or California Household Travel Survey. These studies model how PEVs might be used based on ICEV travel data; they therefore may not be representative of which consumers are likely to buy PEVs, or how consumers may adapt their travel patterns after buying a PEV. Questionnaire surveys have been used to gather information specific to PEVs. These surveys have been administered to members of the general population, new vehicle buyers in general, consumers who have trialled a BEV or PHEV, or consumers who own a BEV. Studies that survey members of the general or new-vehicle-buying population often use stated response methods, including choice experiments and design space exercises to understand how consumer might use PEVs. These studies are not representative of actual behaviours. Surveying consumers who have trialled a PEV for a limited amount of time may reveal more stable information about how consumers perceive or use a PEVs (Jensen et al., 2013) but these studies will still not be representative of how PEVs will be used in the real world. Survey data that are most representative of actual PEV travel behaviour will come from consumers who own a PEV. However, this data is inherently biased in that PEV owners are a self-selecting group, representing only 1–2% of new vehicle buyers in most countries—research shows that such “Pioneers” tend to have significantly different characteristics, including demographics, and purchase motivations (Axsen et al., 2016), though they may have similar travel patterns as the majority of consumers. Further, self-reported PEV usage data can still contain errors, where studies using GPS data will have fewer response errors. GPS studies have been done on ICEVs and on PEVs. Studies that focus on ICEV data will show how consumers travel in general, which may not reveal nuances in the way these consumers use PEVs. GPS data from PEVs shows how consumers use their vehicles and can reveal how, where, and when those consumers charge their vehicles. Finally, studies that monitor how consumers use EVSE reveal information on real world usage of infrastructure. Some of these studies identify when charging occurs, whilst some studies can identify the location of the vehicle that is charging. One limitation of EVSE-based data is that it often does not include vehicle-specific data, which complicates analysis of vehicle usage patterns.

Table 2
Studies used in this paper by author, year, location, methods used, vehicles studied, and the key findings of the publication.

Author(s)	Citation	Year of Publication	Location of study	Methods	Vehicles Studied	Key findings
Axsen and Kurani	Axsen and Kurani (2013)	2013	USA	Questionnaire Survey	PHEV & BEV	Developing more infrastructure may alleviate buyer concerns about PEV driving range.
Axsen et al.	Axsen et al. (2011)	2011	USA	Questionnaire Survey	PHEV	Most PHEV recharging could occur at peak times. In some locations constraining charging to off peak times will result in deeper GHG emission eductions.
Axsen and Kurani	Axsen and Kurani (2012)	2012	USA	Questionnaire Survey		Around 50% of the US population has easy access to level 2 charging from home.
Asxen et al.	Axsen et al. (2017)	2017	Canada	Interviews	BEVs and PHEVs	Current knowledge and awareness of charging for PEVs is low amongst mainstream consumers
Azadfar et al.	Azadfar et al. (2015)	2015	Europe	Literature Review	PHEV & BEV	Uncontrolled charging will lead to increased peak loads. Lower cost off peak charging could prevent this.
Babrowski, et al.	Babrowski et al. (2014)	2014	Europe	Modelling	BEV	Uncontrolled charging could put strain on the grid. Controlled charging could be beneficial.
Bailey and Axsen	Bailey and Axsen (2015)	2015	Canada	Questionnaire Survey	PEVs	Controlled charging has the potential to align charging with the availability of intermittent energy resources. Some respondents expressed concern about loss of control of charging, though on average acceptance rates are high.
Bailey et al.	Bailey et al. (2015)	2015	Canada	Questionnaire Survey		Awareness of PEV charging is low amongst the general population. If consumers are aware of charging infrastructure they may be more likely to purchase a PEV.
Bjornsson and Karlsson	Bjornsson and Karlsson (2015)	2015	Sweden	GPS Data (ICEVs)	PHEV	Optimal battery size differs depending on use pattern. Workplace charging is an important public infrastructure.

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Author(s)	Citation	Year of Publication	Location of study	Methods	Vehicles Studied	Key findings
Burnham et al.	Burnham et al. (2017)	2017	USA	Literature Review	BEV	Charge management is needed to avoid peak power demand issues. Stations should be interoperable and compatible with all PEVs.
California Air Resources Board	California Air Resources Board (2017)	2017	USA	EVSE Data	PHEV & BEV	Most charging occurs at home, followed by work, then DC fast and public locations
Caperello and Kurani	Caperello et al. (2015)	2013	USA	Interviews	PEV (Not defined)	Away from home charging is needed to grow PEV markets. Drivers need to be made aware of infrastructure. Rules or pricing is needed to prevent charge point congestion.
Dong et al.	Dong et al. (2014)	2014	USA	GPS Data (ICEVs)	BEV	eVMT can be increased by public infrastructure. In most locations level 1 infrastructure is preferable due to its low costs. DC will be needed on travel corridors.
Dunckley and Tal	Dunckley and Tal (2016)	2016	USA	Questionnaire Survey	PHEV & BEV	Most PEV drivers charge only at home, with some charging at home and work. Drivers who have ToU tariffs use delayed charging to charge their PEVs.
Ensslen et al.	Ensslen et al. (2017)	2017	Germany and France	EVSE Data and PEV data loggers	BEV	Indirect CO2 emissions from BEV differ significantly between countries but depend also on charging times. Smart charging could be used to reduce emissions from PEV charging.
Figenbaum	Figenbaum (2017)	2016	Norway	Questionnaire Survey	PHEV & BEV	75% of households have private parking and charging. BEV charging only adds 15% to household energy use.
Figenbaum and Kolbenstvedt	Figenbaum and Kolbenstvedt (2016)	2016	Norway	Questionnaire Survey	PHEV & BEV	BEV owners use ICEVs for longer journeys. Workplace charging encourages consumers to purchase PEVs. DC fast chargers are needed on travel corridors. Level 2 chargers are needed at public locations.

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Author(s)	**Citation**	**Year of Publication**	**Location of study**	**Methods**	**Vehicles Studied**	**Key findings**
Franke and Krems	Franke and Krems (2013)	2013	Germany	GPS Data (PEVs)	BEV	Drivers plugin on average 3 times per week and drive on average 38 km per day. Home charging accounts for 83.7% of charging events. Public charging is indispensable for PEV drivers.
Funke and Plötz	Plötz and Funke (2017)	2017	Germany	Modelling	BEV	500 optimally located fast chargers could support 500,000 PEVs in Germany.
Garcia-Villalobos at al.	Garcia-Villalobos et al. (2014)	2014		Literature Review	PEV (Not defined)	Uncontrolled charging will put strain on the grid due to charging occurring at existing peaks. Off peak or time of use charging is preferential but could create a peak at the beginning of the off-peak time. Smart charging is the most effective way to control charging.
Gnann et al.	Gnann et al. (2016)	2016	Germany	Modelling data from Driving Diaries	PHEV & BEV	10 fast chargers are needed for every 1000 PEVs in Germany. Most DC fast charging will occur from 4 pm to 7 pm which is during the evening peak demand. This could cause local grid issues.
Goebel	Goebel (2013)	2013	USA	Questionnaire Survey	PHEV	Smart charging voids the problems of charging PEVs during evening peak.
Graham-Rowe et al.	Graham-Rowe et al. (2012)	2012	UK	Questionnaire Survey	PHEV & BEV	Infrastructure investment is needed to convince consumers to purchase PEVs.
He et al.	He et al. (2016)	2016	China	Modelling	PEV	Charging stations should as convenient to access as possible.
Heinrichs and Jochem	Heinrichs and Jochem (2016)	2016	Germany	Modelling	PEV	The impact from charging stations on higher grid levels is negligible. Low voltage grid levels might be affected. Controlling the time of charging can prevent this from being an issue.

Author(s)	Citation	Year of Publication	Location of study	Methods	Vehicles Studied	Key findings
Idaho National Laboratory	Idaho National Laboratory (2015)	2015	USA	EVSE Data	EVSE Data	Most charging occurs at home. Away from home charging can increase eVMT. TOU tariffs are effective in shifting charge time to off peak hours.
Jakobsson et al.	Jakobsson et al. (2016b)	2016	Sweden	GPS Data (PEVs)	BEV	GPS measurements on households trialling a BEV for three months show very low changes in average daily driving distances compared to pre-trial measurements.
Jakobsson et al.	Jakobsson et al. (2016a)	2016	Germany and Sweden	GPS Data (ICEVs)	BEV	Two car households may be better suited to BEV adoption as the second car has lower variance in daily driving distance, thus fitting specific range limitations better.
Ji et al.	Ji et al. (2015)	2015	USA	Modelling	BEV	Low range BEV charging demand is mainly within the region and metro areas. Long range BEVs would shift charging to long distance travel corridors.
Jochem et al.	Jochem et al. (2015a)	2015	Germany	Modelling	BEV	77 optimally located charging stations could cover 3569 km of autobahn for 100 km range BEVs
Kelly et al.	Kelly et al. (2012)	2012	USA	Questionnaire Survey	PHEV	Charging events may occur at times that are already times of peak power demand. This could have negative impacts on the grid.
Kullingsjo et al.	Kullingsjo et al. (2013)	2013	Sweden	GPS Data (ICEVs)	PHEV	OEMs should introduce BEVs and PHEVs with several different battery sizes. PHEVs should be promoted before grids are decarbonized, BEVs should be promoted when grids are decarbonized.

Author(s)	**Citation**	**Year of Publication**	**Location of study**	**Methods**	**Vehicles Studied**	**Key findings**
Morrissey et al.	Morrissey et al. (2016)	2016	Ireland	EVSE Data	PEV (not defined)	Most consumers prefer to charge at home during the exiting peak period. Car parks and parking garages were the most popular public charging locations. Fast chargers received the highest use frequencies.
Neaimeh et al.	Neaimeh et al. (2015)	2015	UK	EVSE Data	PEVs (not defined)	Having an extensive network of PEV charging locations can alleviate grid impacts by ensuring PEV charging is spatially and temporally diverse.
Neaimeh et al.	Neaimeh et al. (2017)	2017	UK	EVSE Data & GPS Data (PEVs)	BEVs	Fast chargers can increase BEV VMT and can help consumers overcome perceptions of BEV range.
Nicholas et al.	Nicholas et al. (2017a)	2017	USA	EVSE Data	BEV	DC Fast charging occurs closer to home than previously expected, especially when it is free. Free DC fast charging may shift charging from home to DC fast hargers. DC fast charging should be paid.
Nicholas et al.	Nicholas et al. (2011)	2011	California	GPS Data (ICEVs)	BEV	Public infrastructure will be needed for 3.4–8.3% of PEV journeys. This represent between 30% and 45% of VMT though, due to these being long distance trips.
Nicholas et al.	Nicholas et al. (2017b)	2016	California	GPS Data (PEVs)	PHEV & BEV	PHEVs with c. 40 miles of range achieve similar eVMT as Nissan Leafs. For all PEVs most charging events occur at home for all. Level 2 public charging is also needed. Most charging occurs at 5 pm–12 am without TOU. TOU tariffs shift this from 12 am–8 am.
Nicholas et al.	Nicholas et al. (2013)	2013	California	Questionnaire Survey	BEV	300 mile range BEVs can complete almost all travel. 100 mile BEVs will need local infrastructure. 200 mile BEVs will need inter urban charging.

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Author(s)	**Citation**	**Year of Publication**	**Location of study**	**Methods**	**Vehicles Studied**	**Key findings**
Nicholas et al.	Nicholas and Tal (2014)	2014	California	Questionnaire Survey	PHEV & BEV	Free charging at work can result in unnecessary charging and charge point congestion. This can have a negative impact on purchase intentions. Work charging should be paid.
Nicholas et al.	Nicholas and Tal (2017)	2017	USA	GPS Data (PEVs)	PHEV & BEV	Nissan Leaf drivers don't do long trips (over the range of their vehicle) away from home. Tesla drivers do long trips away from home. More public DC fast charging is needed.
Pearre et al.	Pearre et al. (2011)	2011	USA	GPS Data (ICEVs)	BEV	Increased electricity demand is less problematic to grids than previously thought. This is due to drivers gradually plugging-in in the evening between 5 pm and 12 am. However smart charging is preferable as it would shift charging to off peak time.
Plötz and Funke	Plötz and Funke (2017)	2017	Germany	Questionnaire Survey	PHEV & BEV	Development of public charging infrastructure can increase eVMT of PHEVs and BEVs. With home charging and public infrastructure fleet eVMT could be 95%.
Plötz et al.	Plötz et al. (2017b)	2017	Germany, Sweden, and Canada	GPS Data (ICEVs) and Questionnaire Surveys	PHEV & BEV	The number of days' drivers travel more than 100 km is lower than the general perception.
Plötz et al.	Plötz et al. (2017a)	2017	Germany and USA	GPS data, vehicle logger data	PHEV	PHEVs with c. 40 miles of range can achieve similar eVMT as BEVs with c. 100 miles of range
Santini et al.	Santini et al. (2014)	2014	USA	GPS Data (ICEVs)	PHEV & BEV	Infrastructure at home and workplaces should be developed first. DC fast charging should follow this. Intercity fast charging may be needed but it would be underutilised by short range BEVs.

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Author(s)	**Citation**	**Year of Publication**	**Location of study**	**Methods**	**Vehicles Studied**	**Key findings**
Schäuble et al.	Schäuble et al. (2016)	2016	Europe	Questionnaire Survey	PHEV & BEV	Consumers respond positively to interoperability. Consumers are particularly interested in being able to access all DC fact charging stations.
Schäuble et al.	Schäuble et al. (2017)	2017	Germany	GPS Data (PEVs)	PEV (not defined)	Uncontrolled PEV charging could cause an early morning peak (7 am–8 am), late morning peak (10 am–11 am), afternoon peak (1pm–2 pm), and an evening peak (5–6 pm).
Schey et al.	Schey et al. (2012)	2012	USA	EVSE Data	PHEV & BEV	TOU tariffs are effecting in changing charging behaviour.
Shahraki et al.	Shahraki et al. (2015)	2015	China	GPS Data (ICEVs)	PHEV	Optimal location selection of charging points can increase fleet eVMT by 88%.
Skippon and Garwood	Skippon and Garwood (2011)	2011	UK	Questionnaire Survey	BEV	More charging infrastructure would make consumers more willing to purchase a PEV. After home charging workplace charging was ranked the most likely to influence purchase decisions.
Stark et al.	Stark et al. (2018)	2017	Germany	Interdisciplinary Modelling	PHEV & BEV	Interdisciplinary collaboration and holistic research approaches are necessary for allocating charging stations on city-level efficiently. Charging facilities at workplace are fit well with vehicle usage patterns.
Tal et al.	Tal et al. (2014)	2014	California	Questionnaire Survey	PHEV & BEV	Low range PHEVs achieve less eVMT due to the short range and because drivers do not plugin. Addition of work charging can have significant impact on eVMT.
Tal et al.	Tal et al. (2013)	2013	California	Questionnaire Survey	PHEV & BEV	BEVs drive lower miles per year than ICEVs. A reason for this is because of the lack of DC Fast charging infrastructure

Author(s)	**Citation**	**Year of Publication**	**Location of study**	**Methods**	**Vehicles Studied**	**Key findings**
Weiller	Weiller (2011)	2011	USA	Modelling	PHEV	PHEV charging will only put modest pressure on grids. Charging away from home is needed to increase the eVMT of PHEVs. This may include having to charge PHEVs during peak times.
Xydas et al.	Xydas et al. (2016)	2016	UK	EVSE Data	PEVs (not defined)	Most charging occurs between 9 am and 3 pm at the stations considered in the study
Yang et al.	Yang et al. (2015)	2015	China	Questionnaire Survey	BEV	Charging station location and charge time have a significant impact on consumer decision processes. Consumers select stations with the shortest charge time than are close to their origin and along the route of travel.
Zhang et al.	Zhang et al. (2011)	2011	USA	Questionnaire Survey	PHEV	Home charging could result in a peak 6 pm–9 pm. PEV charging should be delayed to off peak times.

2.2. Charge point activity and locations

Charging opportunities are derived from PEV owners' travel patterns. There are four main locations at which charging occurs; (1) at or near home (usually overnight), (2) at workplaces or commute locations (e.g. a transit hub), (3) at publicly accessible locations other than work (e.g. grocery stores, shopping malls), and (4) on travel corridors where drivers stop between the trip origin and destination during long-distance travel (Idaho National Laboratory, 2015; Ji et al., 2015; Nicholas et al., 2017b; Nicholas and Tal, 2014).

Based on the average number of charging events around 50–80% of all events for BEVs and PHEVs occur at home (California Air Resources Board, 2017; Franke and Krems, 2013). Several questionnaire survey studies have found that having access to charging at home is the most influential location in encouraging consumers to purchase PEVs (Bailey et al., 2015; Dunckley and Tal, 2016; Nicholas and Tal, 2017; Plötz and Funke, 2017; Skippon and Garwood, 2011). Home location charging can include private charge points and public charging infrastructure in residential areas. After home charging work or commute location charging is the most frequently used infrastructure according to data from questionnaire surveys with consumers who own PEVs or who have driven them in trials (Bjornsson and Karlsson, 2015; Figenbaum and Kolbenstvedt, 2016; Nicholas and Tal, 2014; Skippon and Garwood, 2011). When BEV owners commute in their vehicle on average 15–25% of charging events occur at work. PHEVs tend to charge at work less, though work charging has been shown to increase eVMT (electric vehicle miles travelled), which is the number of miles that are driven on electricity rather than with the ICE (Nicholas and Tal, 2014). Public and corridor charging stations are the least used infrastructure type. Single digit percentages (around 5%) of charging events occur at these locations. However, these charging events can still be important for longer journeys and can be perceived as a safety net for other charging options (Dong et al., 2014; Morrissey et al., 2016; Nicholas et al., 2017a; Plötz and Funke, 2017; Tal et al., 2014). These locations are used more frequently by BEVs compared to PHEVs. For PHEVs, the number of times the vehicle is plugged into charge is inversely proportional to its electric driving range according to data from California Air Resources Board (2017).

DC fast chargers are being rolled out in many regions as public charging stations. Placement of these chargers is dependent on which vehicles use the infrastructure. According to data from PEV drivers in the USA (Nicholas et al., 2017b) and Norway (Figenbaum and Kolbenstvedt, 2016) short range BEVs are unlikely to undertake long distance travel, but longer ranges BEVs are. For short range BEVs DC fast charge points are used mostly at intra urban locations. For longer range BEVs charge points may be used mostly at inter urban locations (Ji et al., 2015; Nicholas et al., 2013; Yang et al., 2015). A UK study analysed data from EVSE and from GPS tracked BEVs, finding that fast charging infrastructure can increase the VMT in BEVs. This was partly because the infrastructure helped overcome actual range issues allowing drivers to complete more journeys beyond the range of their vehicles. Drivers were also more willing to travel longer distances within the driving range of their vehicles as the charging infrastructure acted as a safety net they could use in the event they might need to charge due to unforeseen circumstances (Neaimeh et al., 2017). There is significant uncertainty in efforts to determine the optimal location of DC fast chargers, data can be taken from several sources including GPS travel behaviour data (Dong et al., 2014; Santini et al., 2014), questionnaire survey data (Dunckley and Tal, 2016; Weiller, 2011), and from use data from DC fast chargers (Ji et al., 2015). Depending on the source of data different results for infrastructure planning may emerge. Fig. 1 from Nicholas et al. (2017a) shows how the desired location of DC fast chargers, as measured by distance from PEV drivers home, can vary depending on the data used. The study analysed data from GPS tracked ICEVs, surveys of PEV buyers, and from EVSE. The study shows that desired locations from survey data are the furthest from home, optimal locations based on GPS data are slightly closer to home, and actual use data from DC fast chargers indicates charging occurs far closer to home than is optimal or desired. This suggests that consumers anticipate that they will charge further away from home than they do in reality.

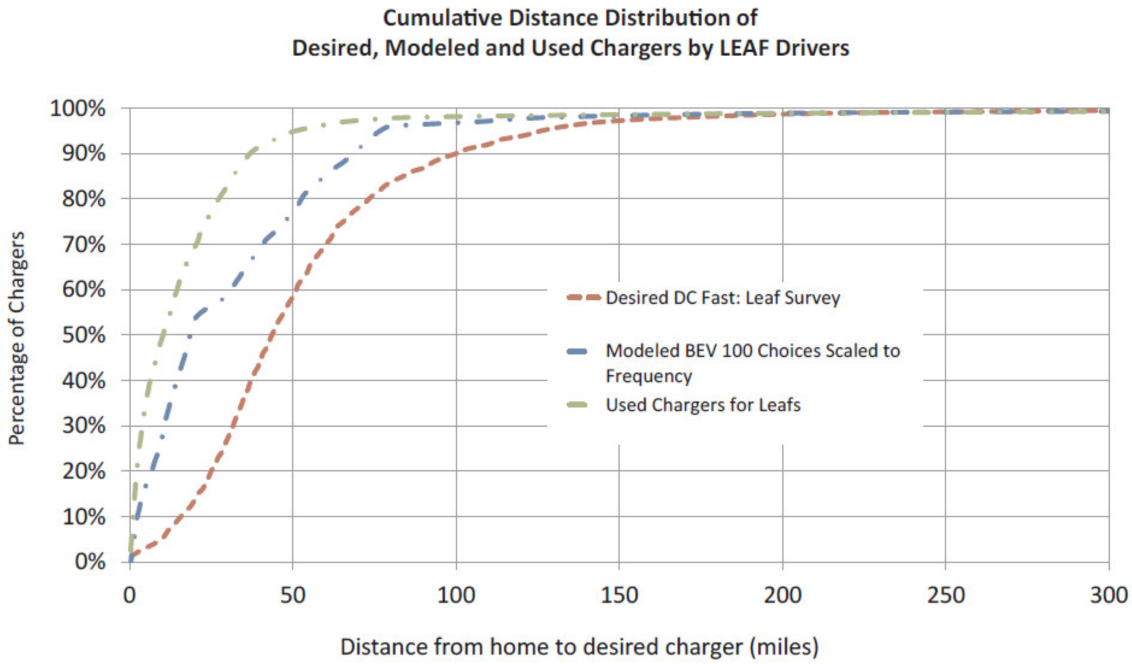

Fig. 1: Data from Nicholas et al. (2017a) showing differences in the desired, modelled, and actual location of DC fast charging events. DC fast charging occurs closer to home that where consumers desire or the optimal based on modelling of 100 mile BEVs.

One final issue associated with PEV charging was first identified by Tal et al. (2013). Their analysis of GPS tracked PEVs in California found that some adopters of PHEVs do not plug-in their vehicles at all. Drivers of PHEV with around 10 miles of driving range typically plugged their vehicles in less. Whilst the vehicles can be driven without being charged this causes the vehicles to have lower than expected efficiencies and a low proportion of eVMT. A Norwegian study also reported that only 16% of PHEV drivers plug their vehicle in every day (Figenbaum and Kolbenstvedt, 2016). However, a recent, broader analysis of PEV usage data estimates that PHEVs have tended to be substantially powered by grid electricity rather than gasoline (Plötz et al., 2017a). Results from this study which contains several data sets totalling more than 70,000 PHEVs with around 40 miles of driving range found that they can achieve similar eVMT as BEVs with 100 miles of range.

2.3. Pricing and interoperability

Consumers typically need to use a membership card to access public charging stations. Currently there are several different charging infrastructure providers, sometimes more than 20 different providers in a region. If consumers wish to access all stations, they may be required to hold a membership card for each company. This situation can cause difficulties for consumers and can be a barrier to them purchasing a PEV (Living Lab Smart Charging, 2017). To reduce complexity policymakers and charging infrastructure companies are finding ways to ensure PEV owners can access any charging station, regardless of membership status (He et al., 2016). This has been done in the Netherlands and Portugal, is a requisite for public charging in Germany, and has been proposed as a legislation in the UK.

Empirical data investigating consumers and interoperability is limited. The first study to investigate this issue was the CROME project in Germany and France which began in 2011 with a trial of 100

BEVs. These vehicles could be charged at fully interoperable charging stations in the region of the trial (Schäuble et al., 2016). Results indicated that consumer respond positively to interoperability. The most important consideration for respondents was the possibility to access fast charging at public locations. In Norway, the Norwegian EV Association has issued RFID cards to their members that can be registered with the main charging infrastructure providers and used at any location. Lorentzen et al. (2017) found that 61% of PEV owners preferred this method of payment. Consumers believed this was an easier than other solutions. An earlier study that surveyed PEV drivers also found this to be the case (Figenbaum and Kolbenstvedt, 2016). Charge points are also being developed with phone identification (e.g. Android Pay, Apple Pay, Google Wallet) credit/debit card readers, or via using SMS payments (Burnham et al., 2017).

Another potential barrier for consumers is the lack of clear information on how payments work (Kurani et al., 2016). Payments for charging usually include one or more components: a onetime connection fee, charge time based payments, kWh based payments, or charging cost based on parking cost. This is significantly different from refuelling a conventional vehicle where consumers are aware of exactly what they are paying, and how much each unit of fuel costs.

2.4. Cost to charge

Previous studies have shown that a common purchase motivation and benefit of owning a PEV is low operating costs compared to ICEVs (Bühler et al., 2014; Dumortier et al., 2015; Hardman et al., 2016; Hardman and Tal, 2016; Hidrue et al., 2011; Peters and Dütschke, 2014; Rezvani et al., 2015). For PEVs to retain this benefit the cost to charge a PEV, or cost per mile to drive a PEV, should be lower than that of an ICEV. Time of use (TOU) and smart charging tariffs can be used to further lower the cost to charge a PEV (explored in 2.6). In many cases free charging is offered to consumers, whilst this can be an incentive to purchase the vehicles (Hardman, 2017), it can have negative consequences, including charge point congestion (Nicholas and Tal, 2014). Typically the only BEV and PHEV drivers that use this free infrastructure are ones who can complete their days driving without recharging (Nicholas et al., 2013; Nicholas and Tal, 2014). BEV owners who would need to charge to complete their daily travel may not risk driving their PEV if they perceive charge point congestion to be an issue or if they think charge points could be inoperable. These two studies indicate that most cases of low dependability are due to congestion at the chargers, rather than from missing infrastructure or low technical reliability. Investing in more infrastructure to eliminate charge point congestion can be costly and may not be practical especially with level 2 or DC Fast chargers. The authors suggest that pricing and policies that limit shifting of home charging to public charging could be part of the solution.

Nicholas et al. (2017a, 2017b) found that free DC fast charging may encourage consumers to charge when they do not need to. Consumers may substitute overnight home charging for free DC fast charging at peak power demand times. This can also be problematic for PEV driers who need to use the fast chargers as they cannot access charging when they need it most.

2.5. Number of public charging stations

Fig. 2 shows PEV stock, number of slow chargers, and number of DC fast chargers in the top 10 PEV nations, where the global average is 153 chargers per 1000 PEVs: 97 slow chargers per 1000 PEVs, and 56 fast chargers. In Norway, a nation where most consumers have home charging, there are 61 chargers per 1000 PEVs. The United States has a similar number of consumers with off street parking, and has 72 chargers per 1000 PEVs. In China and the Netherlands most consumers do not have home charging access. In China, there are 217 charge points per 1000 PEVs and in the Netherlands, there are 239 charger points per 1000 PEVs.

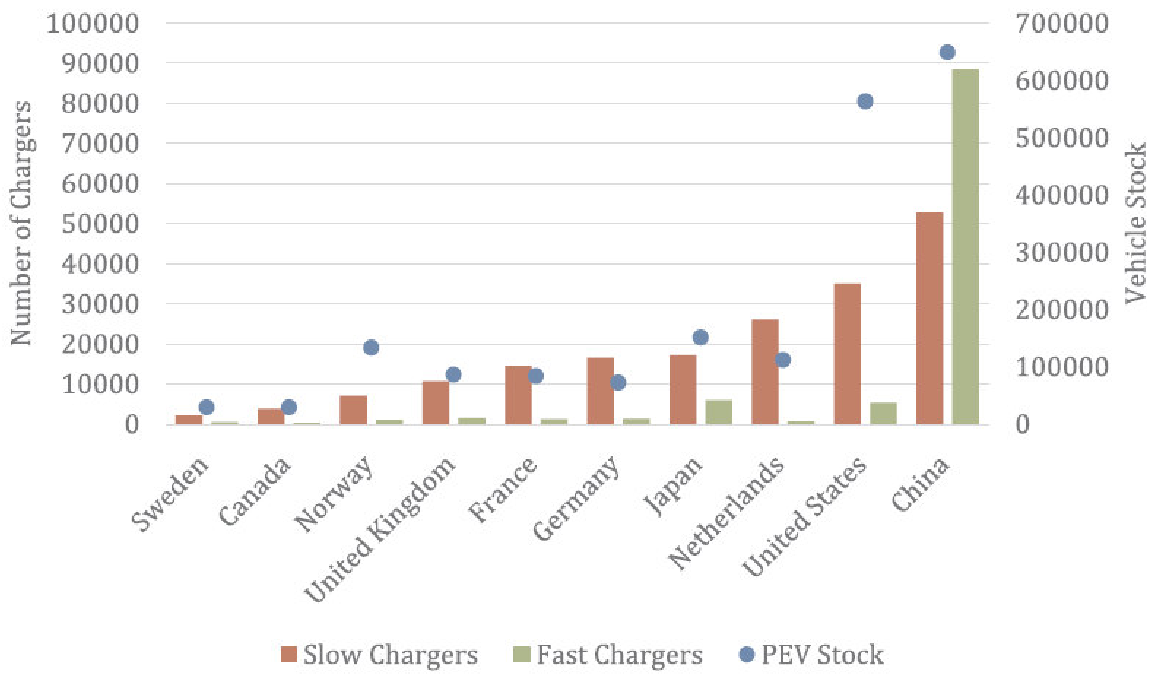

Fig. 2: Fig. 2. Number of public slow (level 1–2) and DC fast chargers, and number of PEVs registered in the top 10 PEV markets. The number of charging stations differs between regions, and is related to the number of PEVs, travel patterns, housing type and other factors associated with local market conditions (International Energy Agency, 2017).

Few studies have worked towards understanding how many charging locations are needed to support PEV roll out. The optimal number of public charging locations may depend upon factors such as the number of workplace chargers, access to home charging (often dictated by housing type), travel patterns, and the market share of PHEVs and BEVs. Three studies from Germany have made suggestions on how many charging locations are needed. Jochem et al. (2015b) modelled travel data in Baden-Württemberg and Bavaria in Germany to determine charging station needs for the autobahn network in that region. They found that 77 optimally located chargers could cover the 3569 km of roads in that region for BEVs with 100 miles of range. Gnann et al. (2016) developed a model to determine public charging infrastructure needs in Germany, form their model they found that 10 chargers may be sufficient for every 1000 PEVs. Finally Funke and Plötz (2017) used data from 6339 travel diaries to determine the number of DC fast chargers needed in Germany. Their results indicated that just 500 chargers could support 500,000 PEVs.

In some regions, most households have their own dedicated off-street parking space on a driveway or in a garage. This is the case in Norway where 75% of households have their own dedicated parking (Figenbaum, 2017) and in California where over 80% of new car buyers can park their car in their garage or driveway (Kurani et al., 2016; Tal et al., 2013). Another study found that more than half of new vehicle-buyers in the US park their vehicle within 25 feet of a level 1 charging opportunity (Axsen and Kurani, 2012). However, in many other regions (e.g. China or Netherlands), a higher proportion of drivers are unable to do this: they park their vehicles on the street, in off street public parking lots, or in private parking lots. Consumers in these regions may not have easy access to home charging, this can be a barrier to them purchasing the vehicles. According to several studies consumers perceive a lack of charging at home as a one of the greatest barriers to them purchasing a PEV (Ajanovic and Haas, 2016; Axsen et al., 2015; Axsen and Kurani, 2013; Figenbaum and Kolbenstvedt, 2016; Nilsson and Nykvist, 2015).

2.6. Temporal distribution of charging and charge management

Studies using GPS data from ICEVs and data from EVSE have found that due to the initial low numbers of PEVs in most regions, charging is unlikely to have negative impacts on the grid for some time (Babrowski et al., 2014; Pearre et al., 2011; Schey et al., 2012). However, with greater numbers of PEVs large numbers of vehicles charging at the same time in the same area could impact the low-voltage grid (Gnann et al., 2016; Schey et al., 2012). On a regional scale charging many PEVs at the same time could cause peak power demand events (Azadfar et al., 2015; Kelly et al., 2012; Morrissey et al., 2016; Schäuble et al., 2017). The current literature suggests that with uncontrolled charging consumers are likely to charge their PEVs when they arrive at work, in pubic locations in the evening, and when they arrive home in the evening or night-time. Questionnaire surveys have also found that consumers are likely to charge their vehicles at a similar time as one another, and that this time may corresponded to an existing demand peak (Axsen et al., 2011; Schäuble et al., 2017; Zhang et al., 2011). These findings suggest that when PEVs are deployed in large numbers they could cause a demand spike at several times throughout the day particularly in the morning and evening. It has been suggested that charging could be managed to prevent this, especially as vehicles have significant flexibility in when they charge as they parked for long periods of time (particularly overnight) (Sadeghianpourhamami et al., 2018).

A method of controlling home charging, and something that is being used at present in California, USA, is TOU domestic electricity tariffs (PG&E, 2017; SMUD, 2015). At off-peak hours (often at night), consumers pay a lower electricity rate. During peak times (often in the day), they pay a higher electricity rate. Households are incentivised to charge their vehicles at night. In some cases, additional metering equipment is required for consumers to have TOU tariffs. A study in California administered a questionnaire survey to owners of PEVs to understand their charging behaviour, and whether they have and use TOU rates. The study found that consumers who had TOU rates chose to charge their vehicles in the lower priced off peak time (Dunckley and Tal, 2016). In the UK, a time of use type tariff has been in use since 1978 for domestic electricity. This system is known as economy 7, which provides 7 h of off-peak electricity (British Gas, 2017). The off-peak rates are usually around 50% of the peak rate. According to Hamidi et al. (2009) these tariffs, which 16% of UK consumers subscribe to, have also been effective in shifting demand to the off-peak time. These studies indicate that pricing mechanisms may be effective in managing when consumers use electricity.

Smart charging is a more advanced system of managing charging. This involves managing PEV charging based on current electricity supply, electricity demand, and driver needs. According to Garcia-Villalobos et al. (2014) and Goebel (2013) smart charging could be an effective system in preventing peaking events from occurring. Smart charging can be implemented at home, public, and work charging locations. At DC fast chargers it may not always be possible to utilise smart charging, due to some PEV drivers wanting to charge their vehicles quickly. According to data from the Netherlands, where smart charging is being implemented, the system can allow existing electricity grids to support ten times more PEVs compared to uncontrolled charging (GreenFlux, 2017; Living Lab Smart Charging, 2017). The system in the Netherlands limits charging through communication between the charge point and back of office software. When charging needs to be reduced the current (amps) delivered to the vehicle is reduced. On the other hand, during periods of low demand and high supply, PEVs can charge freely. Smart charging has been found to be beneficial to the grid and most consumers have been willing to accept this method of charge management in the Netherlands (Living Lab Smart Charging, 2017). A study using surveys and interviews with mainstream car buyers found that they are less willing to accept smart charging (Bailey and Axsen, 2015). The study did find that some consumers were willing to enrol in smart charging schemes including ones that utilise renewable energy. Interviewees expressed concern over having less control over the how their vehicle is charged though (Axsen et al., 2017).

Neaimeh et al. (2015) found that having more charging locations increases the spatial and temporal distribution of PEV charging. They suggest increasing the amount of infrastructure as a demand management strategy. Recent literature reviews of controlled charging suggest that more research is needed to understand mainstream consumer acceptance of such programs (Sovacool and Axsen, 2017).

2.7. Information, education, and outreach

According to questionnaire surveys and interviews mainstream car buyers' knowledge and awareness of PEV recharging infrastructures is currently low (Axsen et al., 2017; Bailey et al., 2015; Kurani et al., 2016). The only consumers who have a high awareness of charging infrastructure are consumers who have purchased a PEV or ones interested in purchasing one. Members of the general population who have not purchased a PEV are less knowledgeable about their potential charging options. According to Bailey et al. (2015) only 18% of mainstream car buyers had seen a public EV charger. Questionnaire survey data from California found that between 2013 and 2017, despite a doubling the number of charging stations deployed, no more consumer claimed to have seen a single PEV charger (Kurani, 2017).

Studies have found that low awareness is correlated with low intentions to purchase a PEV. However, it is unclear if increased awareness of charging infrastructure will increase intent to purchase a PEV—statistical analysis indicates a weak or non-existent relationship (Bailey et al., 2015). In other studies, increasing knowledge of infrastructure amongst PEV adopters led to increased use of charge points, which increases the overall electric miles driven by the vehicles (Caperello et al., 2015; Kurani, 2017; Kurani et al., 2016).

3. Summary & conclusion

This review provides an overview of different types of methods and sources of data, each of which have different strengths and weaknesses. Here we work to glean several insights from the reviewed studies, whilst acknowledging that there is significant uncertainty in even present trends and usage, and even more uncertainty in understanding future usage patterns and relationships among variables (e.g. charging availability and PEV uptake). This paper provides 5 key insights relating to; (1) the importance of infrastructure at home, work, and public locations, (2) consumers access to charging infrastructure, (3) the cost to charge a PEV, (4) how many charge points are needed to support the introduction of PEVs, and (5) the impact of charging on power grids and management of this. These insights are outlined in more detail below.

First according to existing evidence home location charging is the most important piece of infrastructure in convincing consumers to purchase a PEV and is the most frequently used charging location (Bailey et al., 2015; Dunckley and Tal, 2016; Franke and Krems, 2013; Nicholas and Tal, 2017; Plötz and Funke, 2017). Workplace charging has been found to be the second most influential charging location in convincing consumers to purchase a PEV it is also the second most frequently used charging location (Bjornsson and Karlsson, 2015; Figenbaum and Kolbenstvedt, 2016; Nicholas and Tal, 2014; Skippon and Garwood, 2011). Public charging stations appear to be the least frequently used locations but are still important in encouraging consumers to purchase PEVs (Dong et al., 2014; Morrissey et al., 2016; Neaimeh et al., 2017; Nicholas et al., 2017a; Plötz and Funke, 2017; Tal et al., 2014).

Second, at present, consumers may have difficulties in charging their vehicle at all locations due to the lack of compatibility with all infrastructure. Research indicates that increasing interoperability of charge points is perceived positively from the perspective of consumers (Figenbaum and

Kolbenstvedt, 2016; Lorentzen et al., 2017; Schäuble et al., 2016). Increasing interoperability may lead to increased PEV sales and increase the VMT of PEVs.

Third a key purchase motivator for the buyers of PEVs is their low running costs (Bühler et al., 2014; Dumortier et al., 2015; Hardman et al., 2016; Hardman and Tal, 2016; Hidrue et al., 2011; Peters and Dütschke, 2014; Rezvani et al., 2015). The low running costs of PEVs are due to low maintenance costs and low charging costs. The cost to charge a PEV should be lower than the refueling cost of conventional vehicles if PEVs are to retain the benefit of low running costs. Free charging has been implemented in some regions, especially at workplaces. Studies have shown that this can incentivise consumers to purchase the vehicles but may have unwanted consequences (Hardman et al., 2017; Nicholas and Tal, 2014). Free charging may lead to BEV and PHEV drivers charging their vehicles unnecessarily which can cause all charge points to become occupied which is especially problematic for BEVs.

Fourth research into how many charge points are needed to serve consumers is currently limited to a small number of studies in Germany (Funke and Plötz, 2017; Gnann et al., 2016; Jochem et al., 2015b). These have found that around 10 fast charges for every 1000 PEVs may be sufficient. Wide conclusions on the number of charging stations needed cannot be drawn from those studies alone meaning the number of charging locations needed is currently unknown.

Finally the early market introduction of PEVs appears unlikely to impact electricity grids due to the comparatively low number of vehicles deployed (Babrowski et al., 2014; Pearre et al., 2011; Schey et al., 2012). However large numbers of PEVs may cause disruption to the local grid (Gnann et al., 2016; Schey et al., 2012) and cause power demand increases on a regional scale (Azadfar et al., 2015; Kelly et al., 2012; Morrissey et al., 2016; Schäuble et al., 2017). Using pricing mechanisms such as TOU tariffs and smart charging to manage when consumers charge has been found to prevent these issues from occurring (Dunckley and Tal, 2016; Garcia- Villalobos et al., 2014; Goebel, 2013). Evidence relating to how consumers interact with smart charging is still limited, with one study indicating consumer may respond negatively to losing control of when their vehicle is charged (Axsen et al., 2017).

3.1. Policy implications

The development of charging infrastructure should be a part of a more general policy of promoting electric vehicles. Developing infrastructure alone will not be sufficient to ensure the market entry success of PEVs. Policymakers could seek to introduce incentives to lower the purchase price of PEVs which may encourage consumers to purchase the vehicles (Hardman et al., 2017; Mersky et al., 2016; Sierzchula et al., 2014; Vergis and Chen, 2015; Zhou et al., 2016). Increasing consumer awareness of PEVs may also increase their likelihood of purchasing a PEV (Bailey et al., 2015; Bühler et al., 2014; Krause et al., 2013; Turrentine et al., 2011). It is also possible to introduce policies that encourage automotive OEMs to supply PEVs to regions, for example with the use of a mandate as is the case in California (Sperling and Eggert, 2014; Vergis and Mehta, 2010).

The findings of this review can be used to inform policymakers, as well as charging infrastructure providers, OEMs, and any stakeholders involved with the transition to PEVs. Infrastructure development is important for increasing PEV sales and encouraging and facilitating consumers to use PEVs more frequently. As home location chargers appear to be the most important piece of infrastructure in encouraging consumers to purchase PEVs (Bailey et al., 2015; Dunckley and Tal, 2016; Nicholas and Tal, 2017; Plötz and Funke, 2017; Skippon and Garwood, 2011) publicly accessible home location infrastructure may need to be developed in regions with households that do not typically have off street parking. This will include on street charging and charging in off street car parks such as those in apartment complexes. In addition to workplace chargers, chargers in public locations, and DC fast chargers may be needed to encourage the purchase and use of PEVs, especially BEVs (Dong et al., 2014; Morrissey et al., 2016; Nicholas et al., 2017a; Plötz and Funke, 2017; Tal et al., 2014). Access and payment to this charging infrastructure should be as simple as possible and could be harmonised across regions to increase the interoperability of infrastructure for consumers (Figenbaum and Kolbenstvedt, 2016; Lorentzen et al., 2017; Schäuble et al., 2016). This infrastructure should not be free to use as this can cause unnecessary charge point congestion which can lead to consumers being less likely to purchase and use PEVs (Nicholas and Tal, 2014). Ensuring there is a cost to charge can prevent PEV drivers from charging unnecessarily thus benefitting BEV drivers who need to charge. Finally, the time that PEV drivers charge could be managed to prevent negative impacts to the grid. Existing evidence suggests that pricing strategies can shift charging to the off peak period and consumers are willing to use these tariffs (Dunckley and Tal, 2016; Hamidi et al., 2009). A more advanced and technically complex method to control charging is via smart charging. Smart charging may be able to shift more charging events to off peak times than TOU tariffs (Garcia-Villalobos et al., 2014; Goebel, 2013). Consumers may be willing to use smart charging, however there is uncertainty on how consumers will respond to this system (Bailey and Axsen, 2015).

3.2. Limitations and further research needs

This paper only focuses on charging infrastructure from a consumer perceptive rather than a technical (e.g. charge point design) or environmental perspective (e.g. emissions from the electricity generated for PEV charging). It also does not consider other aspects associated with a transition to PEVs. The benefit of focusing on one topic is an in-depth look at one important issue. This review does not consider the impact of V2G (bi-directional smart charging), this is due to literature in that area currently lacking empirical data on how consumers respond to this technology, how they use it, or whether they would use it (Sovacool et al., 2017). The study does not consider how electrified autonomous vehicles might use charging infrastructure nor does it consider the recharging of shared vehicles or vehicles in transit network companies (e.g. Uber or Lyft). The paper also does not consider the needs of traditional transit or of taxi fleets due to the different use cases of these vehicles. Understanding the infrastructure needs of transit network companies, transit companies, and taxi fleets is an important area of future research. Helping policymakers and transit companies understand the charging needs of their vehicles may bring about increased electrification in the transit sector.

Currently most literature on PEV recharging is based on studies of BEVs with around 100 miles of driving range. As the transition to PEVs continues more vehicles with 200 miles of range will be delivered to consumers. Future studies need to assess infrastructure needs of these vehicles as it may differ to the needs of the current stock of BEVs. On one hand 200 mile BEVs may be even more reliant on home location charging which could reduce the need for work and public charging. On the other hand, BEVs with 200 miles of range could travel longer distances and require more public infrastructure. Early data from (Nicholas et al., 2017b) shows that the travel behaviour of BEVs with more than 200 miles of range may be similar that of conventional vehicles. This suggest that 200 mile BEVs may travel more thus needing more DC fast charging infrastructure. Funke and Plötz (2017) though found that DC fast charging infrastructure needs will reduce as BEV range increases. More studies of this nature are needed so that an understanding of what infrastructure is needed to support the transition to longer range BEVs into the future. One of the most severe limitations of the literature is that the number of charging stations needed is currently unknown. This research needs to be conducted in many different regions including Europe, North America, and Asia to understand how much infrastructure is needed. There are currently few studies on the impact of interoperability or lack of it. Studies could investigate the extent to which this is an issue for consumers, and what positive impacts increased interoperability could have on purchase intentions and eVMT.

A present DC fast chargers mostly have charge rates of around 40–120 kW. Ultra-fast DC fast chargers with outputs of 150–350 kW have been installed by some charge point companies (EVgo, 2017). At present these can only charge vehicles up to 150 kW, but have the potential to charge at 350 kW when vehicle and battery technology can take this level of power. Some OEMs have suggested that future vehicles will be able to charge at 350 kW (Porsche, 2018). Research could be undertaken to understand how this infrastructure would be used by consumers. This could include payment for charging, location of charging, at what time charging occurs, and any impacts these ultra-fast charges may have on electricity grids.

The market introduction of PEVs is currently restricted to around 1–2% of buyers in most nations. Even in Norway, where PEVs have reached more than one third of new car sales, most buyers are still typical early adopters (Figenbaum, 2017). These consumers are known to behave differently (Rogers, 2003), it is unlikely that these consumers have vastly different infrastructure needs as most car buyers have similar travel patterns. However, research into how mainstream consumers will use PEVs is still needed.

It is the hope of the authors that addressing the areas of future research suggested above will work towards gathering the information needed to ensure the transition to more electrified transportation is successful.

Acknowledgements

The authors of this manuscript are members of the International EV Policy Council, a global policy initiative coordinated by the Plug-in Hybrid & Electric Vehicle Research Center, of the Institute of Transportation Studies, University of California Davis. The council is funded by ClimateWorks Foundation.

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