Considerations for the development of plug-in electric vehicle charging infrastructure for consumers- A review

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Abstract
Plug-in electric vehicles (PEVs) need to be adopted by large numbers of consumers to have a significant impact on urban air pollution, climate change, and resource depletion. The adoption of PEVs is partially dependent on the availability of PEV charging infrastructure. The development of this infrastructure needs to be carefully considered so that it serves the needs of PEV buyers and encourages more consumers to purchase the vehicles. This article draws from data in the current literature to make recommendations on charging location, charging levels (level 1, 2, DC fast), access and payment for charging, pricing, dependability of infrastructure, charge management, and number of charging stations. To ensure PEV market entry is successful infrastructure will be needed at home locations, workplaces, and in public locations. Charging level should be based on location, with home and work being level 1 or 2, and public being level 2 or DC fast. Charge stations should be interoperable so that all consumers can access them, and there should be a cost to charge to prevent unnecessary charging and congestion of chargers. Charging should be managed with smart charging or pricing tariffs that prevent peak demand charging. Finally, the number of charging stations needed in a region will depend on several factors including PEV market share, travel patterns, and housing types.
1. Introduction
Plug-in electric vehicles (PEVs) are more efficient and less polluting than the majority of internal combustion engine vehicles (ICEVs)\textsuperscript{1–3}. They will need to increase market shares to have an impact on urban air pollution, energy consumption, and climate change. The success of the technology is partially reliant on the development of recharging infrastructure. While PEVs can be recharged from standard plug sockets, these socket charge PEVs slowly and are not always easily accessible by vehicles. Developing, dedicated infrastructure will encourage more consumers to purchase PEVs and allow them to drive more electric miles\textsuperscript{4–15}. The development of this infrastructure should be carefully considered so that the benefits of infrastructure development can be maximized. PEV charging infrastructure should be developed by policy makers, OEMs, utilities, workplaces, housing developers, charging infrastructure companies, and any other stakeholders. Policy makers have some ability in ensuring the correct infrastructure is deployed and can regulate how infrastructure is deployed. There are currently no studies published that review existing research to provide information on the considerations for the development of PEV recharging infrastructure. This papers’ contribution is most holistic outline of this literature. It takes evidence from studies that use questionnaire surveys\textsuperscript{10,16–24}, interviews\textsuperscript{12,25}, GPS data from ICEVs\textsuperscript{26–32}, GPS data from PEVs\textsuperscript{33–36}, data from electric vehicle supply equipment (EVSE)\textsuperscript{37–41}, and from studies that construct models based on national or regional travel surveys (e.g. California Household Travel Survey)\textsuperscript{42–44}.

2. Lessons from Academic Research & Empirical Data
In the following sections this paper provides information from studies on charging levels, charge point location, charge point access and payment, cost to charge, considerations for households without off street parking, the required number of charging stations, charge point dependability, charge management, and implications for public transit. Table 1 shows the authors, year of publication, location of study, methods used, and key findings of the studies used in this review.
Table 1: Studies used in this paper by author, year, location, methods used, and the key findings of the publication.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Location</th>
<th>Methods</th>
<th>Key findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axsen and Kurani</td>
<td>2013</td>
<td>USA</td>
<td>Questionnaire Survey</td>
<td>Developing more infrastructure may alleviate buyer concerns about PEV driving range.</td>
</tr>
<tr>
<td>Axsen et al.</td>
<td>2011</td>
<td>USA</td>
<td>Questionnaire Survey</td>
<td>Most PHEV recharging could occur at peak times. Constraining charging to off peak times will result in deeper GHG emission reductions.</td>
</tr>
<tr>
<td>Azadfar et al.</td>
<td>2015</td>
<td>Europe</td>
<td>Literature Review</td>
<td>Uncontrolled charging will lead to increased peak loads. Lower cost off peak charging could prevent this.</td>
</tr>
<tr>
<td>Babrowski, et al.</td>
<td>2014</td>
<td>Europe</td>
<td>Modelling</td>
<td>Uncontrolled charging could put strain on the grid. Controlled charging could be beneficial.</td>
</tr>
<tr>
<td>Bjornsson and Karlsson</td>
<td>2015</td>
<td>Sweden</td>
<td>GPS Data (ICEVs)</td>
<td>Optimal battery size differs depending on use pattern. Workplace charging is an important public infrastructure.</td>
</tr>
<tr>
<td>Burnham et al.</td>
<td>2017</td>
<td>USA</td>
<td>Literature Review</td>
<td>Charge management is needed to avoid peak power demand issues. Stations should be interoperable and compatible with all PEVs.</td>
</tr>
<tr>
<td>California Air Resources Board</td>
<td>2017</td>
<td>USA</td>
<td>EVSE Data</td>
<td>Most charging occurs at home, followed by work, then DC fast and public locations.</td>
</tr>
<tr>
<td>Caperello and Kurani</td>
<td>2013</td>
<td>USA</td>
<td>Interviews</td>
<td>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.</td>
</tr>
<tr>
<td>Dong et al.</td>
<td>2014</td>
<td>USA</td>
<td>GPS Data (ICEVs)</td>
<td>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.</td>
</tr>
<tr>
<td>Dunckley and Tal</td>
<td>2016</td>
<td>USA</td>
<td>Questionnaire Survey</td>
<td>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.</td>
</tr>
<tr>
<td>Figenbaum</td>
<td>2015</td>
<td>Norway</td>
<td>Questionnaire Survey</td>
<td>75% of households have private parking and charging. BEV charging only adds 15% to household energy use.</td>
</tr>
<tr>
<td>Figenbaum and Kolbenstved</td>
<td>2016</td>
<td>Norway</td>
<td>Questionnaire Survey</td>
<td>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.</td>
</tr>
<tr>
<td>Franke and Krems</td>
<td>2013</td>
<td>Germany</td>
<td>GPS Data (PEVs)</td>
<td>Drivers plug in on average 3 times per week and drive on average 38km per day. Home charging accounts for 83.7% of charging events. Public charging is indispensable for PEV drivers.</td>
</tr>
<tr>
<td>Funke and Plötz</td>
<td>2017</td>
<td>Germany</td>
<td>Modelling</td>
<td>500 optimally located fast chargers could support 500,000 PEVs in Germany.</td>
</tr>
<tr>
<td>Garcia-Villalobos at al.</td>
<td>2014</td>
<td></td>
<td>Literature Review</td>
<td>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.</td>
</tr>
<tr>
<td>Gnann et al.</td>
<td>2016</td>
<td>Germany</td>
<td>Driving Diaries</td>
<td>10 fast chargers are needed for every 1000 PEVs in Germany. Most DC fast charging will occur.</td>
</tr>
<tr>
<td>Source</td>
<td>Year</td>
<td>Location</td>
<td>Method</td>
<td>Conclusion</td>
</tr>
<tr>
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<tr>
<td>Goebel</td>
<td>2013</td>
<td>USA</td>
<td>Questionnaire Survey</td>
<td>Smart charging voids the problems of charging PEVs during evening peak.</td>
</tr>
<tr>
<td>Graham-Rowe et al.</td>
<td>2012</td>
<td>UK</td>
<td>Questionnaire Survey</td>
<td>Infrastructure investment is needed to convince consumers to purchase PEVs.</td>
</tr>
<tr>
<td>He et al.</td>
<td>2016</td>
<td>China</td>
<td>Modelling</td>
<td>Charging stations should be as convenient as possible.</td>
</tr>
<tr>
<td>Idaho National Laboratory</td>
<td>2015</td>
<td>USA</td>
<td>EVSE Data</td>
<td>Most charging occurs at home. Away from home charging can increase eVMT. TOU tariffs are effective in shifting charge time to off peak hours.</td>
</tr>
<tr>
<td>Jakobsson et al.</td>
<td>2016</td>
<td>Sweden</td>
<td>GPS Data (PEVs)</td>
<td>Most consumers can use PEVs on most days. PEV drivers need to adopt their travel on 0-3.6 days per month.</td>
</tr>
<tr>
<td>Jakobsson et al.</td>
<td>2014</td>
<td>Germany and Sweden</td>
<td>GPS Data (ICEVs)</td>
<td>Two car households may be better suited to PEV adoption as ICE can be used for longer trips.</td>
</tr>
<tr>
<td>Ji et al.</td>
<td>2015</td>
<td>USA</td>
<td>Modelling</td>
<td>Low range BEV charging demand is mainly within the region and metro areas. Long range BEVs would shift charging to long distance travel corridors.</td>
</tr>
<tr>
<td>Jochem et al.</td>
<td>2015</td>
<td>Germany</td>
<td>Modelling</td>
<td>77 optimally located charging stations could cover 3569km of autobahn for 100km range BEVs.</td>
</tr>
<tr>
<td>Kelly et al.</td>
<td>2012</td>
<td>USA</td>
<td>Questionnaire Survey</td>
<td>Charging events may occur at times that are already times of peak power demand. This could have negative impacts on the grid.</td>
</tr>
<tr>
<td>Kullingsjo et al.</td>
<td>2013</td>
<td>Sweden</td>
<td>GPS Data (ICEVs)</td>
<td>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.</td>
</tr>
<tr>
<td>Morrissey et al.</td>
<td>2016</td>
<td>Ireland</td>
<td>EVSE Data</td>
<td>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.</td>
</tr>
<tr>
<td>Neaimeh et al.</td>
<td>2015</td>
<td>UK</td>
<td>EVSE Data</td>
<td>Having an extensive network of PEV charging locations can alleviate grid impacts by ensuring PEV charging is spatial and temporally diverse.</td>
</tr>
<tr>
<td>Nicholas et al.</td>
<td>2017</td>
<td>USA</td>
<td>EVSE Data</td>
<td>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 chargers. DC fast charging should be paid.</td>
</tr>
<tr>
<td>Nicholas et al.</td>
<td>2011</td>
<td>California</td>
<td>GPS Data (ICEVs)</td>
<td>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.</td>
</tr>
<tr>
<td>Nicholas et al.</td>
<td>2016</td>
<td>California</td>
<td>GPS Data (PEVs)</td>
<td>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 5pm-12am without TOU. TOU tariffs shift this from 12am-8am.</td>
</tr>
<tr>
<td>Authors</td>
<td>Year</td>
<td>Location</td>
<td>Methodology</td>
<td>Findings</td>
</tr>
<tr>
<td>--------------------</td>
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</tr>
<tr>
<td>Nicholas et al.</td>
<td>2013</td>
<td>California</td>
<td>Questionnaire Survey</td>
<td>300 mile range BEVs can complete almost all travel. 100 mile BEVs will need local infrastructure. 200 mile BEVs will need inter urban charging.</td>
</tr>
<tr>
<td>Nicholas et al.</td>
<td>2014</td>
<td>California</td>
<td>Questionnaire Survey</td>
<td>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.</td>
</tr>
<tr>
<td>Nicholas et al.</td>
<td>2017</td>
<td>USA</td>
<td>GPS Data (PEVs)</td>
<td>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.</td>
</tr>
<tr>
<td>Pearre et al.</td>
<td>2011</td>
<td>USA</td>
<td>GPS Data (ICEVs)</td>
<td>Increased electricity demand is less problematic to grids than previously thought. This is due to drivers gradually plugging-in in the evening between 5pm-12am. However smart charging is preferable as it would shift charging to off peak time.</td>
</tr>
<tr>
<td>Plötz and Funke</td>
<td>2017</td>
<td>Germany</td>
<td>Questionnaire Survey</td>
<td>Development of public charging infrastructure can increase eVMT of PHEVs and BEVs. With home charging and public infrastructure fleet eVMT could be 95%.</td>
</tr>
<tr>
<td>Plötz et al.</td>
<td>2014</td>
<td>Germany, Sweden, and Canada</td>
<td>GPS Data (ICEVs) and Questionnaire Surveys</td>
<td>The number of days’ drivers travel more than 100km is far lower than drivers perceive.</td>
</tr>
<tr>
<td>Santini et al.</td>
<td>2014</td>
<td>USA</td>
<td>GPS Data (ICEVs)</td>
<td>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 underutilized by short range BEVs.</td>
</tr>
<tr>
<td>Schäuble et al.</td>
<td>2017</td>
<td>Germany</td>
<td>GPS Data (PEVs)</td>
<td>Uncontrolled PEV charging could cause an early morning peak (7am-8am), late morning peak 10am-11am, afternoon peak 1pm-2pm, and an evening peak 5-6pm.</td>
</tr>
<tr>
<td>Schey et al.</td>
<td>2012</td>
<td>USA</td>
<td>EVSE Data</td>
<td>TOU tariffs are effecting in changing charging behaviour.</td>
</tr>
<tr>
<td>Shahraki et al.</td>
<td>2015</td>
<td>China</td>
<td>GPS Data (ICEVs)</td>
<td>Optimal location selection of charging points can increase fleet eVMT by 88%.</td>
</tr>
<tr>
<td>Skippon and Garwood</td>
<td>2011</td>
<td>UK</td>
<td>Questionnaire Survey</td>
<td>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.</td>
</tr>
<tr>
<td>Tal et al.</td>
<td>2014</td>
<td>California</td>
<td>Questionnaire Survey</td>
<td>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.</td>
</tr>
<tr>
<td>Tal et al.</td>
<td>2013</td>
<td>California</td>
<td>Questionnaire Survey</td>
<td>BEVs drive lower miles per year than ICEVs. A reason for this is because of the lack of DC Fast charging infrastructure</td>
</tr>
<tr>
<td>Weiller</td>
<td>2011</td>
<td>USA</td>
<td>Modelling</td>
<td>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.</td>
</tr>
<tr>
<td>Xydas et al.</td>
<td>2016</td>
<td>UK</td>
<td>EVSE Data</td>
<td>Most charging occurs between 9am-3pm at the stations considered in the study</td>
</tr>
</tbody>
</table>
2.1. Charging Levels

Depending on the charging level it is possible to charge a PEV at different speeds (Table 2). The slowest charge is from level 1 chargers. Level 1 charging is only done in nations with 110-120v grid power (e.g. USA). Using standard plug sockets these charge a PEV with 100 miles of range in around 24 hours and are mostly used for overnight charging at home. Level 1 can also be sufficient at workplaces due to long dwell times of vehicles here. Level 2 (208-240v) 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 hours. 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). They have very high power demands, due to the high kW power outputs of the charge points, therefore it may not be wise to consider these as the main charging option for most PEVs. These chargers should be installed in locations where consumers need to recharge their PEV quickly, such as on travel corridors. In Europe chargers are also designated based on their communication protocol. Either mode 1, 2, 3, or 4 charging is possible. This topic is not considered in this paper.

There are also several types of charge point connectors. Most PEVs use a standardized connector for level 2 charging (J1772). For DC fast charging, several different connectors are currently in use (e.g. CHAdeMO, CCS). Most PEVs can use these chargers (sometimes with an adapter) but Tesla fast chargers (also known as Superchargers) are only accessible by Tesla vehicles. Any lack of compatibility prevents consumers from accessing all charging locations. In Spain, all charge points are required by law to have multiple charge point connector types. Even when OEMs install their own charge points, they must install charge connectors for all PEVs from all other OEMs.

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage, Amps</th>
<th>Typical location</th>
<th>Time to charge 100 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>110v, 20A,</td>
<td>Home</td>
<td>24 hours</td>
</tr>
<tr>
<td>Level 2</td>
<td>240v, 20A</td>
<td>Home, Work, Public</td>
<td>10 hours</td>
</tr>
<tr>
<td>Level 2</td>
<td>240v, 100A</td>
<td>Work, Public</td>
<td>2 hours</td>
</tr>
<tr>
<td>DC Fast</td>
<td>240v-480v, 2 or 3 phase 20A-200A AC</td>
<td>Corridor</td>
<td>&lt;15 minutes</td>
</tr>
</tbody>
</table>
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. The location of a charging event is often correlated with a single use case. However, in many cases the same charging station is used for many different uses. A charger may be a public charger for some PEV drivers, while for others it is a travel corridor charger, or a workplace charger.

Around 75-85% of all PEV charging occurs overnight at home. Having access to charging at home has been found to be the most influential charge location in encouraging consumers to purchase PEVs. Home location charging can include private charge points and public charging infrastructure in residential areas. Work or commute location charging is the most frequently used infrastructure after home charging. When people commute in their PEV around 15-25% of charging occurs at work. Work charging has been shown to increase eVMT and can encourage more consumers to purchase PEVs. 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 are still important because they are used for longer journeys and as a safety net for other charging options. In the early stage of PEV market entry policy makers may have to support the rollout of public and corridor charging infrastructure as, due to the low number of PEVs, there may not be a viable business case. Chargers should become profitable as PEVs increase market shares and use the infrastructure.

Public and corridor charge points should be situated at locations where drivers already stop: near rest areas, cafés, restaurants, shopping malls, etc. In addition to these being areas people visit they are likely to be locations that are correlated with existing grid infrastructure that could support charging. Placement of DC fast charging locations is dependent on which PEVs use the infrastructure. For short range PEVs DC fast charge points will be needed mostly at intra urban locations. For longer range PEVs (200 miles and more) charge points will be needed mostly at inter urban locations.

When stakeholders are considering the location of DC fast chargers data can be taken from several sources including GPS travel behavior data, questionnaire survey data, and from use data from DC fast chargers. Depending on the source of data different results for infrastructure planning may emerge. Figure 1 shows significant variation in charge point location depending on the source of data. This study used data from GPS tracked ICEVs to model optimal charge point locations, from survey data of PEV buyers who were asked where at which locations they would desire DC fast chargers, and from EVSE data which shows actual use behavior of DC fast chargers. The study shows that desired locations are the furthest from home, optimal locations (based on GPS data) are slightly closer to home, and actual use of DC fast chargers occurs far closer to home than is desired or has been modelled. For this reason, stakeholders should use several sources of data if they want to make the most effective infrastructure planning decisions.
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 purchasing a PEV. To reduce complexity for consumers, policy makers and charging infrastructure companies should find ways to ensure PEV owners can access any charging station, regardless of membership status. 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. PEV drivers who do not have any membership status should also be able to access charge stations. This can be done with charge points having phone identification (e.g., Android Pay, Apple Pay, Google Wallet) or credit/debit card readers.

Another major barrier for consumers is the lack of clear information on how payments work. 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 refueling a conventional vehicle where consumers are aware of exactly what they are paying, and how much each unit of fuel costs. A clear system that helps drivers to understand the cost per kWh and the derived cost per mile will help users make the best economic decision regarding the time and location of their charging events. Finally, charging speed (level 1, 2, DC fast) is not usually guaranteed and in many cases not clearly marked. Charging stations should indicate this information to consumers.

2.4. Cost to charge

A common purchase motivation and benefit of owning a PEV is their low operating costs compared to ICEVs. 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 2.7 Charge management). In many cases free charging is offered to consumers, while this can be an incentive to purchase the vehicles, it can have negative consequences 19,64.

BEV owners are less likely to use their car if they cannot depend on public charging. This is particularly problematic when charge points become congested 19. In these cases, the only PEV drivers that use the infrastructure are ones who can complete their days driving without recharging. 19,51. According to Nicholas et al. 19,51 PEV owners who would need to charge to complete their daily travel do not risk driving their PEV if they perceive charge point congestion to be an issue or if they think charge points could be inoperable. According to those studies most cases of low dependability are due to congestion at the chargers, though low dependability can stem 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 DC Fast chargers. Pricing and policies that limit shifting of home charging with public charging could be part of the solution.

Workplace charging is often provided for free for reasons including the desire to offer an employee perk, the low business value of charging, the high cost of administrating a paid system, and because it can encourage PEV sales 19,36,65. Free work charging can encourage consumers to recharge even when they do not need to do so. This may cause chargers to be congested (meaning there are more EVs wanting to charge than there are charge points), which shifts night charging to the daytime peak and causes businesses to install more chargers. Studies have shown that pricing workplace charging to a similar amount as home charging can alleviate congestion and prevent people from charging when they don’t need to 19,66. Free DC fast charging may also 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. Charge point congestion can be problematic for PEV drivers who need to use the fast chargers. DC fast charging should only be used by consumers when they need to charge their vehicle quickly 33. Pricing could be used to manage when consumers use these chargers.

2.5. Households without off street parking
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 67 and in California where over 80% of new car buyers can park their car in their garage or driveway 16,56. However, in many other regions (e.g. China, Netherlands), drivers are unable to do this: they park their vehicles on the street, in off street public parking, or in private parking lots. Infrastructure will be needed for these consumers, this includes on street charging, charging in public parking spaces, and charging in private parking spaces. If infrastructure is not developed for these consumers the PEV market may be unable to grow beyond a certain size, as these consumers may perceive lack of charging as a significant barrier to them purchasing a PEV 5,21,68.

2.6. Number of public charging stations
The number of public charging stations required to support PEV charging depends 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. Figure 2 shows PEV stock, number of slow chargers, and number of DC fast chargers in the top 10 PEV nations.
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. The global average is 153 chargers per 1000 PEVs. This is 97 slow chargers per 1000 PEVs, and 56 fast chargers. Studies from Germany have suggested that only 10 DC fast charge locations are needed for every 1000 PEVs, though this is dependent on optimal placement of the chargers.

![Figure 2](image.png)

Figure 2: Number of 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.

2.7. Charge management

The early introduction of PEVs is unlikely to have negative impacts on the grid due to the relatively low numbers of vehicles being charged. With greater numbers of PEVs, charging may need to be managed to ensure it does not negatively impact the low-voltage grid or cause peak power demand events. With uncontrolled charging consumers are likely to charge their PEVs when they arrive at work, in public locations in the evening, and when they arrive home in the evening or nighttime. Large numbers of PEVs charging at these times may cause a demand spike at times when power demand is already high. Charging can be managed to prevent this from occurring. BEVs have significant flexibility in when they charge since they parked for long periods of time (particularly overnight).

A method of controlling home charging, and something that is being used at present, is to give consumers TOU domestic electricity tariffs. 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 therefore incentivized to charge their vehicles at night. In California TOU rates have shifted charging to night times, suggesting this is an effective method to change consumer charging behavior. Different regions may require different TOU structures depending on local conditions. Utilities and policy makers may need to assess their local grid infrastructure, generation mix, and supply and demand profiles before defining on
and off-peak periods. Even within each region different tariffs may be needed due to the possibility of a peaking event if many PEVs begin charging at same off-peak time. Utilities should provide TOU tariffs with the off-peak period beginning over a range of times (e.g at 10 pm, 11 pm, 12 am, 1 am, etc.).

Smart charging involves managing PEV charging based on current electricity supply, electricity demand, and driver needs. Smart charging can be more effective at home, public, and work charging locations. At DC fast chargers it may not always be possible to utilize smart charging, due to some PEV drivers wanting to charge their vehicles quickly. According to data from the Netherlands smart charging can allow existing electricity grids to support ten times more PEVs compared to uncontrolled charging. 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 consumers have been willing to accept this method of charge management. In the Netherlands, a long-term strategy of ensuring that all chargers are smart chargers is being implemented. Smart charging is easier to implement than V2G and offers almost as many of the benefits to the electricity grid. At smart charging locations consumers, should be able to opt out of smart charging in case they want to immediately charge their PEV. This should be at a higher cost than the cost to charging using smart charging. One strategy to prevent peaking events and negative impacts to local grids is to develop more infrastructure. Having more charging in more locations increases the spatial and temporal distribution of PEV charging.

2.8. Information, Education, and Outreach

Information, education, and outreach programs can be used to educate consumers about PEV infrastructure. Consumers will be encouraged to buy PEVs if they are more aware of their charging options. Education increases the use of charge points by PEV owners, which increases the overall electric miles driven by PEVs. The development of charging infrastructure should be a part of a more general policy of promoting electric vehicles. At present the only consumers who have a high awareness of charging infrastructure is consumers who have purchased a PEV. Consumers who have not purchased a PEV are less knowledgeable about their potential charging options. Signposting infrastructure locations has been shown to increase consumer awareness and knowledge of infrastructure locations. This can increase utilization by PEV owners and can lead to more PEV sales.

3. Conclusion

The information presented in this paper is drawn from a large body of literature. The results can be used by policy makers, charging infrastructure providers, OEMs, and any stakeholders involved with the transition to PEVs. Data from modelling studies, case studies, studies that use GPS data, questionnaire surveys, and data from charge points are used to make the following conclusions and recommendations. The most important piece of infrastructure for consumers is home chargers (or chargers near to PEV drivers’ homes), these charges are used most frequently and have the greatest impact on the decision to purchase a PEV. Workplace chargers, chargers in public locations, and DC fast chargers are also important in encouraging consumers to purchase and use PEVs. Charging level (level 1, 2, DC fast) should be optimized based on charge point location. Level 1 or 2 should be at locations with long dwell times, DC fast should be at locations with short dwell times. Access
and payment for charging should be as simple as possible and should be harmonized across regions. Prior to determining the number of charging stations needed policy makers need to assess local conditions (housing type, number of PHEVs and BEVs, etc.). For consumers to purchase and use PEVs they need to be confident that they can depend on accessing chargers. Pricing strategies can be yes to ensure that infrastructure is dependable. The time that consumers charge should be managed with smart charging or TOU tariffs. This will ensure charging does not coincide with existing electricity demand peaks. Finally, more opportunities for PEV drivers to charge increases spatial and temporal distribution of charging events, this can mitigate any negative impacts to the grid. The development of infrastructure will encourage more consumers to purchase PEVs, thus driving the market. It will ensure consumers who have purchased PEVs use them as frequently as possible which will maximize their proportion of miles driven that are electric miles.

3.1. 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 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. However other measures are needed to ensure PEV market entry is successful. Consumer incentives may be needed to encourage the adoption of PEVs. These include purchase incentives, measure such as free parking, unrestricted car pool lane access, toll fee waivers, etc.

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. Currently much of the 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 available to consumers. Future studies will need to access infrastructure needs of these vehicles as it may differ to the needs of the current stock of BEVs.
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