Renewable and Sustainable Energy Reviews 154 (2022) 111733

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The state of play in electric vehicle charging services – A review of infrastructure provision, players, and policies

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ARTICLE INFO

Keywords:
Electric vehicles (EVs)
Charging infrastructure
Energy policy
EV markets
Transport decarbonisation
Energy economics

ABSTRACT

This paper reviews the market for electric vehicle (EV) charging infrastructure; it focuses on the types of existing charging, the main functions and actors in the market and the future policy actions required for widespread expansion. Electric vehicles represent a key technology in the mitigation of transportation greenhouse gas emissions and ambitious EV adoption targets have been set by many governments by 2030 and beyond. The rollout of EV charging infrastructure is vital in achieving this goal, as the uptake of EVs is linked to the level of coverage of EV chargers. To date, both the public and private sectors have been involved in the provision of charging stations and it is timely to consider the roles of the different actors in this market. We consider whether EV charging infrastructure is a public good or private asset and address the issues of the location of future chargers, the deployment models needed to develop, operate and own charging infrastructure, and finally the policy context for the development of charging infrastructure. We find that clear roles should be assigned to the individual public and private actors and funders, in order to achieve efficient development of the required infrastructure for large-scale EV deployment.

1. Introduction

Decarbonisation of transportation is a critical component of governments' efforts to reduce greenhouse gas emissions in support of climate mitigation goals. Electrification of vehicle fleets, particularly in countries with increasing shares of renewable electricity supply, represents a key pathway toward low-carbon mobility. Electric mobility can also help to alleviate urban air quality hazards, which are increasingly driving state and local policy action [1]. Policies aligned with these environmental objectives, as well as rapidly dropping technology costs, have led national governments and automakers to make considerable commitments to future electric vehicle (EV) deployment in recent years.[2] Uptake has also increased in several markets: according to the International Energy Agency's (IEA) Global EV Outlook for 2019, there were more than 5.1 million electric vehicles worldwide in 2018, increasing by 2 million on the previous year. Based on existing commitments and announced new targets, the IEA forecasts continued growth in EV market share, with a global stock of total exceeding 130 million by 2030 [2].[3]

While predictions for future EV adoption point to ambitious growth, a successful, comprehensive transition will need to be supported by robust vehicle charging infrastructure. EV ownership requires that drivers have access to both public and home charging infrastructure so that they can feel confident in transitioning to EV ownership without fear that their driving behaviour will be curtailed due to refuelling limitations. Empirical studies, such as Sierzchula et al. [3]; show that per capita public charging infrastructure is the best indicator of national EV market share, with a higher impact on EV uptake compared with financial incentives. They show that adding an extra charging station per 100,000 residents resulted in approximately double the impact on EV

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2 While some country targets are non-specific, the focus of deployment targets is generally on battery electric vehicles but does not necessarily exclude plug-in hybrid EVs (for example, see Ref. [106] for French targets). The UK has included hybrid vehicles in its ban on internal combustion engine vehicles [107]. Major manufacturers such as Volkswagen, Volvo, Ford, BMW, Renault-Nissan, and more have increased EV production targets (see Refs. [108,109]; and [8]).

3 These projections are aligned with the IEA's central New Policies Scenario assumptions. The more ambitious EV30@30 scenario forecasts a global EV stock of 250 million by 2030.

https://doi.org/10.1016/j.rser.2021.111733
Received 10 February 2020; Received in revised form 15 August 2021; Accepted 28 September 2021
Available online 3 November 2021
1364-0321/

market share compared with providing an additional $1000 in consumer financial incentives. More recently, Hall and Lutsey [4] find a significant relationship demonstrating that increasing the number of charge points per capita is associated with increased electric vehicle adoption.[4] Others find that the causality between charging infrastructure and EV ownership is less clear [5,6].

The market for EV charging is in its early stages, and considerable uncertainty remains as to how charging services should be provided, as well as which policies are best suited to support deployment. The regulatory frameworks, government incentives, commercial actors, and resulting business models in place to support EV charging vary widely both across and within jurisdictions. There has been little focus in the literature on the existing market for EV charging, compared with analysis of the policies to encourage uptake of EVs. We therefore review how EV charging infrastructure has been deployed, supported, and financed in a range of countries and regions. We aim to address the following broad questions:

- How and where do drivers prefer to charge, and what is the strategic role of different types and locations of charging services?
- What deployment models are currently in place for developing, operating, and owning charging infrastructure? What are the underlying cost and revenue drivers of EV charging stations?
- Which approaches have governments used to support deployment of charging infrastructure, and what role can policy and incentives play in this area?

We focus primarily on discussion of the EU, US, and Chinese markets to derive relevant and practicable examples of market-driven policy interventions. Findings presented here are largely based on academic literature and policy reports, however, given the dynamic nature of the Electric Vehicle Supply Equipment (EVSE) market, these sources have been supplemented with media coverage to ensure relevance and accuracy.

The review is structured according to the following topics: Section 2 details different modes and locations of public charging infrastructure, and how customers tend to use each. Section 3 provides an overview of business models EV charging, identifying the key functions in provision of charging infrastructure as well as the underlying economics of charging service providers. Section 4 outlines the role of government and policy in charging infrastructure, including public funding and incentives for deployment, regulatory policies with respect to network ownership, and managing potential grid impacts. Section 5 concludes with summary observations and policy recommendations.

2. Electric vehicle charging infrastructure overview: type, location, speed

In broad terms, it is clear that charging availability is a critical enabling factor for EV deployment. EV charging is also available at different speeds, costs, and locations and these must be tailored to fit drivers' needs. The strategic roles of various charging modes, in particular, home charging, publicly-accessible charging, and charging at work are important considerations for policy makers and market actors to optimise charging deployment. This subsection, we present the findings on how and where the various types of charging are used by EV residential customers.

2.1. Charging modes

Definition of charging levels is highly variable across academic, policy, and market literature and across country/region. We refer here to charging ratings using the terminology of Level 1 (slow charging), Level 2 (slow to fast charging using AC), or Direct Current Fast Charging (DCFC). An alternative rating system, more commonly used in Europe, refers to charging mode 1 (slow), mode 2 (slow to semi-fast using AC), mode 3 (semi-fast to fast using AC) and mode 4 (DC fast charging).[5] Fig. 1 demonstrates the high-level alignment between Levels I, II, and DCFC and the four charging modes.

2.2. Home charging

Charging at home tends to be the most common approach for EV recharging and comprises level 1 or level 2 chargers. Many countries often subsidies to EV purchasers to install a Level 2 charger in their home. Drivers' ability to install home charging is dependent upon whether they have access to a dedicated, off-street parking spot, typically a driveway or garage. For example, approximately 80% of Swedish electric car users live in individual houses, compared with only 50% of the general population [7].

EV drivers rely heavily on private charging under current market conditions. In Norway, where the electric car market is most advanced in terms of market share, there is one public charger for every 19 EVs on the road [8]. Behavioural studies and aggregate data regarding charging location indicate the dominance of home charging over other locations; a few examples are provided in Table 1, below, and more detailed data are available for Norway (see Ref. [9] and Sweden (see Ref. [10].

However, EV ownership is often concentrated in urban or densely populated areas – as in Norway, where this demographic accounts for 90% of EV owners [13], and the US, where 82% of EV sales in 2015 occurred in the 50 most populous metropolitan areas [14]. In the UK, surveys indicate that while approximately 70% of households have garages or off-street parking, suggesting that a high proportion of future charging demand could be delivered through residential infrastructure, the percentage falls to only 30% in urban centres [15]. A high share of urban residents living in apartment-style housing may also lead to a shortage of access to off-street parking and EV charging, which could inhibit EV uptake.

2.3. Public charging

Home charging has been a sensible and efficient solution particularly for early EV adopters in the absence of widespread public charging installations. However, the prevalence of home charging under current market conditions should not lead policymakers to conclude that public charging infrastructure is not important for uptake. Indeed, during early market stages, the role of public and workplace charging may be undervalued by considering only the proportion of charging events that occur in each type of location. Rather, frequency of charging events (rather than volume) can show that even those drivers who charge mainly at home do access public charging networks for some journeys. Public charging stations consist of level 2 and DC fast chargers. While Level 2 charging stations can be located where vehicle owners are parked for long periods of time, such as shopping centres, airports, hotels, government offices, and other businesses, fast chargers are found more frequently along highway corridors [16].

In Europe, the Alternative Fuels Infrastructure Directive (AFID) (EU/2014/94) required EU members to set deployment targets for publicly accessible chargers for 2020, 2025 and 2030, with an indicative ratio of

[4] These factors are also discussed, if not quantified, in Refs. [110,111]; and [54].

[5] Charging ratings are set out by standard-setting bodies: in North America, the Society of Automotive Engineers (SAE) has defined charging levels for both AC and DC charging, while in Europe, the industry observes the four charging modes defined by the International Electrotechnical Commission (IEC). However, common definitions of these standards vary in policy and academic literature, and we therefore use common terminology rather than strict industry standards.

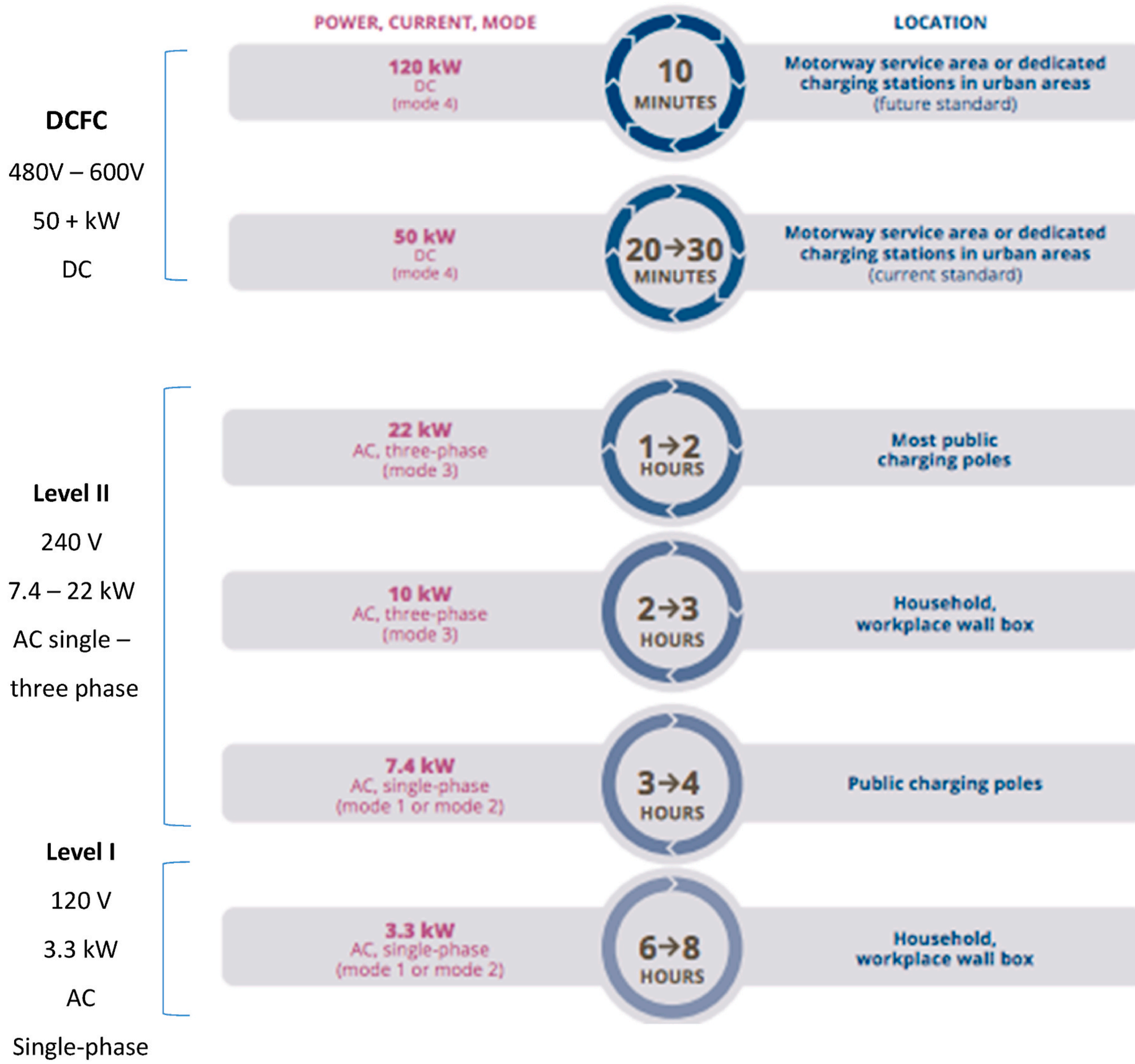

Fig. 1. Charging rating comparison for 100 km of driving range*.

Table 1
Distribution of charging by location: examples in literature.

Jurisdiction	Home	Public	Workplace
US [11]	75–85%	~5%	15–25%
Europe (McKinsey, 2013)	80%	5%	15%
UK [12]*	72.5%	18.1% (~12% fast, 6% Level II)	6.7%

*2.8% of charging occurred at locations classified as "other."

1 charger per 10 electric cars. At the start of 2020 the number of publicly accessible charging points in the European Union was around 225,000 or 9 vehicles per charging point [17]. An evaluation of the directive in 2021, however, found that the implementation of charging infrastructure was not consistent across the EU [18,19]. Consequently, a new Regulation is proposed that requires Member states to ensure that for "each battery electric light-duty vehicle registered in their territory, a total power output of at least 1 kW is provided through publicly accessible recharging stations; and (b) for each plug-in hybrid light-duty vehicle registered in their territory, a total power output of at least 0.66 kW is provided through publicly accessible recharging stations" [20].

Qualitative interviews with EV experts in the Nordic region showed that public charging infrastructure was important to increased EV uptake in all four countries in the study, both for peace of mind and genuine need reasons [21]. Figenbaum and Kolbenstvedt [9] found that EV owners in Norway charged most frequently at home or at work using slow chargers. However, the surveys also showed that 60% of battery EV owners used public Level II charging at least monthly or yearly, and 10% used them at least once per week, and 28% accessed fast charging at least monthly. As more drivers without access to dedicated private parking (e.g. multi-unit apartment buildings) purchase EVs, public charging will become more important for this category of users.

Low utilisation of public charging compared with other charging locations (i.e. home and workplace) creates a paradoxical challenge. Drivers prefer to charge at home, where charging is convenient and low-cost. Yet, while their actual charging requirements may be largely satisfied with home charging, drivers still look to public charging networks to provide reassurance that charging will be available to them should they need to access it (Kley et al. [22]; Schroeder and Traber [23]. Neubauer and Wood [24] found that increasing home charging power beyond Level 1 charging (at approximately 1.5 kW DC) had little impact on vehicle utility, but that access to Level 2 public charging infrastructure (at 6.5 kW DC power) dramatically increased total distance travelled, and brought many drivers to near 100% vehicle utility.

At the same time, low utilisation rates make charging infrastructure difficult to operate profitably.

The result is that governments wishing to support public charging network development must consider methods for facilitating efficient, strategic investments that provide necessary infrastructure, conscious of the current challenge in achieving profitability. The high rate of home charging could shift as public charging infrastructure becomes more widely available, and as driver needs and characteristics change with growing EV utilisation. Empirical studies show that utilisation of different types of charging infrastructure changes measurably when EV uptake increases (see, e.g. Ref. [25]. As such, continued analysis of driver profiles and behaviours should help to inform charging investments.

2.4. Workplace charging

Charging at work can provide a critical opportunity for EV drivers who may not have easy access to home charging. Level 2 stations are the most common type of chargers installed in the workplace [16]. A wide-ranging survey in the US found that a cohort of 30% of EV drivers charged only at work on most days [26]. Where primary or sole reliance on workplace charging is possible, employer-located charging availability could be particularly useful for promoting adoption among drivers without access to off-street parking for home charging. Hall and Lutsey [4] provide a helpful overview of workplace charging initiatives, which include up to 50% funding for employers offering free charging from the province of Quebec, 40% of costs per charge point for workplace charging or public charging on-site for French employers, and rebates up to £300 for UK employers installing workplace or fleet charging. Workplace charging can also be helpful in promoting electric vehicle uptake: Garas et al. [27] note the value of peer-to-peer communication as a driver of technology diffusion in general, and note that charging infrastructure located in social settings such as the workplace could help to facilitate EV adoption. Olexsak [28] cites survey data from the U.S. Department of Energy's Workplace Charging Challenge, which indicates employees of companies that provide charging infrastructure are 20 times more likely to purchase an electric vehicle.

An added consideration for workplace charging is its potential to contribute to increased renewable energy utilisation, particularly in jurisdictions that experience an oversupply of clean power generation during daytime hours. One example is California, where large-scale distributed solar generation has led to large dips in daytime net power demand, followed by sharp ramping to meet evening peak load. A high-EV deployment scenario for California estimated that controllable EV charging could avoid approximately 2 GW of renewable curtailment [29]. Similarly, Fang et al. [30] use both average marginal pricing and marginal carbon and pollutant emissions rates to show how the social cost of charging depends on the time incidence of charging events, i.e. when electricity is generated with fossil fuels.[6] Fang et al. [30] therefore note that daytime workplace charging can promote cleaner electricity consumption, and that such behaviour could be encouraged if electricity pricing reflects the social cost of carbon. An alternative perspective is provided by Chakraborty et al. [31] who find that free workplace charging may shift home charging to the workplace, which in turn can cause congestion in the network.

2.5. Role of fast-charging

The location of chargers, whether at home, in public, or at work, is only one dimension for considering charging utility. Charging time and relationship to existing driver preferences and behaviours are also critical to maximizing utilisation and properly aligning charging networks with driver needs. Level 2 public charging stations play an important role in the overall network of charging options for EV drivers, but particularly so when drivers are able to charge over an hour or more without interruption to their travel needs. This could include charging while at work or while spending time shopping, for example. However, fast charging is more practical for drivers concerned with taking longer journeys, upwards of 100 miles or more, during which they may need to refuel their car. It can also be usefully aligned with existing behavioural profiles to meet day-to-day driving needs, for instance when siting fast-charging stations at locations where drivers would typically run a quick errand.

Fast charging can also more closely replicate the refuelling experience of conventional vehicles, potentially providing a more accessible transition for drivers switching to EVs [12,32]. This will be true especially as technology moves beyond current fast charging equipment, which allows for charging between 50 and 120 kW, to charging capacity of 400 kW or higher, allowing for meaningful refuelling within 10–25 min [33]. Here again, however, the economics of fast-charging provision can be challenging, as fast-charging stations are of high importance to users, but may experience low-utilisation rates, leading to poor profitability outcomes [32]. Hundt et al. [34] cite several barriers to public charging adoption in general, such as utilisation uncertainty, hardware costs, installation complexity and cost, and difficultly in assessing revenue models, all of which are exacerbated by the relatively high upfront cost of fast-charging stations (explored in Section 3). Regardless of its initial costs, fast charging will certainly play a critical role in the continued deployment of EVs.

One concern regarding the use of fast charging is whether battery degradation may occur due to overcycling. Lithium-ion batteries generally lose capacity as the battery is repeatedly charged and discharged over time, depending on factors like state of charge and temperature [35]. Availability of fast charging has therefore given rise to concerns that quicker charging times may accelerate the rate at which batteries lose driving range. EV manufacturer Tesla has acknowledged that its battery management system may restrict the rate of EV charging under a range of conditions, including those that indicate high use of fast charging, in order to preserve vehicle range [36]. However, this effect does not appear to be typical for the general EV driving population, as behavioural literature shows that EV owners do not utilise fast charging in a manner that inhibits battery performance. A 2015 NREL study found that drivers typically received 7.6% of energy from fast charging, up to a maximum of 41.5%. Because fast chargers are used infrequently, the impact on battery capacity loss was negligible [37].

Idaho National Laboratory also conducted a small but notable field test exploring the effect of fast-charging on battery life issue comparing two 2012 Nissan Leafs charged twice per day with Level 2 charging and two charged twice per day with 50 kW fast-charger. Impacts on capacity after 10,000 miles driven showed no significant difference; after 50,000 miles driven, there was only 2% difference in battery capacity between the Level 2 and DC fast charged Leafs [38].

3. The charging infrastructure market

Charging infrastructure has historically been developed, owned, and operated by a range of different market actors, including public or semi-state enterprises, as well as private companies. We examine here the value chain for developing and operating EV charging infrastructure, including the functions that the market provides and how different companies participate. We generally consider only approaches employed by actors who have developed or supplied publicly-accessible

[6] This measure reflects the fact that if night time power demand is met by high shares of fossil-fuel generation, then EV charging during the night when electricity is cheap incurs higher social damage via carbon dioxide, nitrogen oxide (NOx), and sulphur oxide (SOx) emissions than lower-emissions daytime charging [30]. examine this situation using Sacramento, California as a case study, and include carbon pricing to determine the most social optimal charging time.

charging networks, rather than those who simply provide or install hardware on an ad-hoc basis. Section 3 also considers the underlying economic factors, including installation costs and payment schemes, that shape the market opportunity for charging provision.

3.1. Key functions

Several studies provide broad discussion of the business model for provision of charging infrastructure (see Refs. [39,40]), however no clear model has yet emerged for delivering this service, and few studies evaluate existing models in detail. For the purpose of clarity in discussing charging companies and their associated networks, we define here four primary functions in the EVSE value chain, drawing on EY [41]; Hall et al. [42]; and Nigro and Frades [43]:

1. Manufacturing: the original equipment manufacturer who produces charging equipment such as mounted home chargers and standalone public charging stations.
2. Installation/Development: arranges and executes installation and sources financing
3. Network Operation: manages and provides maintenance and customer-facing services for the physical network and payment platform.
4. Sales & Marketing: entity that hosts infrastructure, sets payment structure and prices, and/or collects or shares revenues from resale of electricity

A schematic demonstrating the range of functions across which a sample of charging companies engage is shown in Fig. 2, below.

Companies may be organized around only one, or up to all four, of the key functions described above.[7] In terms of single-function market participants, some electronics manufacturers operate in the EV charging market solely in the manufacturing function by producing and supplying hardware (i.e. charging stations). Others, like UK-based Charge Your Car, provide only a platform for network operation, but do not procure, develop, or directly market charging equipment or services to customers.

3.1.1. Charging company business models

Among companies who are active across multiple market functions, the question of asset ownership is a key consideration in evaluating business models and considering prospective policy interactions. Some companies, like ChargePoint and SemaConnect, focus on installing and operating a network of charging stations, but do not retain ownership of the network. Garas et al. [27] label this approach the "network-operator model," in which the company develops and maintains a network, but sells the actual hardware to host sites, which then manage billing and access to charging stations. This model allows host sites to set their own payment structures and fees, and to retain revenues gained, less fees paid to the operator. In such cases, the network operator shifts a large portion of business risk to host entities, who are exposed to both the upfront cost of the EVSE, as well as any fluctuations in future revenues.

Alternatively, some companies, like EVGo and Blink Network, develop, operate, and own their charging networks. Garas et al. [27] call this approach the "owner-operator model," representing a vertically integrated set of functions in which the charging company supplies and owns hardware, manages billing and access, and collects revenues from the infrastructure. The owner-operator model is similar to a traditional mobile telecommunications company that invests in infrastructure and charges clients for the services provided by the infrastructure. In such cases, the network operator may partner with a private host to site charging stations, but retains control over pricing, as well as exposure to revenue risk. While the downside risk due to low utilisation could present a challenge to owner-operators, they may also be better positioned to capitalise on future increases in charging demand or on favourable regulatory shifts compared with network operators described above.

Beyond the owner-operator model are still more integrated approaches, as in the case of companies like Tesla and Aerovironment, which are active across all four market functions, including manufacturing equipment, to installing and managing networks, to collecting revenues, though not necessarily in an integrated format. Under these arrangements, companies must recover their costs for charging infrastructure through user fees. Alternatively, Tesla offers charging for free by including the cost of developing a charging network in the upfront cost of its vehicles. Large equipment manufacturers that produce, own, and operate charging equipment may also find that managing a fully integrated EV value chain does not function well alongside traditional operations. Aerovironment, for example, sold off sold its electric vehicle charging business to German automobile supplier Webasto in June 2018 so that it could continue to focus on its core operations in unmanned aircraft and missile systems.

In addition to these approaches is the separation model, which Tesla and Better Places experimented with in the early years of the last decade. This business model sees a separation between EV and battery, where the vehicle is purchased but the battery is leased. When this battery then needs to be recharged it is merely switched out upon reaching a service station with a fully charged one, thus eliminating the need to wait. The consumer essentially just purchases the charge itself, the battery now becoming a standardized container that is leased as needed. This approach is being revisited by Chinese automakers NIO and BIAC, with the ambition of applying the model in China. As China eases state subsidies to both EV manufacturers and EVSE providers, industry analysts seek new, more profitable ways in which to steer the market. Yang et al. [44] suggests that the separation model could be a viable route and therefore recommends greater cooperation between the state and the companies involved, along with a standardisation in battery design. This model is still at a fledgling stage, yet given that China is the largest EV market on the planet, that it still suffers issues of profitability, and that the state is reducing the level of financial aid, then this radical approach might at least merit greater analysis.

There are a number of different business models operating within China. The state-owned China Grid Corporation, the second largest provider there, follows the owner-operator model. However, the largest EV charging station provider, TGOOD, is akin to Tesla in that they manufacture, install, and operate charging equipment and stations. TGOOD dominates the market in China and is therefore likely one of the largest providers of such a service globally [45]. Large auto manufacturers, such as BYD and SAIC, again follow the Tesla model but hold a comparatively smaller share of the market. The Chinese market is relatively crowded, but there are regional monopolies [46]. Business models in China are quite similar to what can be seen around the world, the biggest difference is in the overwhelming support of the state-provincial, municipal, or central government - either through subsidies, regulations or state-owned enterprises. Also, the second and fourth largest EVSE providers, State Grid and Potevio, are state-owned.

3.1.2. Ownership of charging point host sites

Charging points can be hosted by a range of different commercial or public actors who wish to provide charging access as an amenity on their property, as a benefit to their employees, or both. An early survey of charging locations in New York state found that retail and city centre locations made up a combined 24% of publicly-accessible charging stations, and sites such as commercial offices, universities, hospitals, and transport centres all had less than 7% each. The survey found that a plurality of charging points (41%) were located either at car dealerships or at petrol stations [47].

[7] Companies that provide direct end-customer services are often referred to as Electromobility Service Providers (EMSPs), however given the variability in the other functions EMSPs may perform, this report does not apply the general "EMSP" terminology for charging companies.

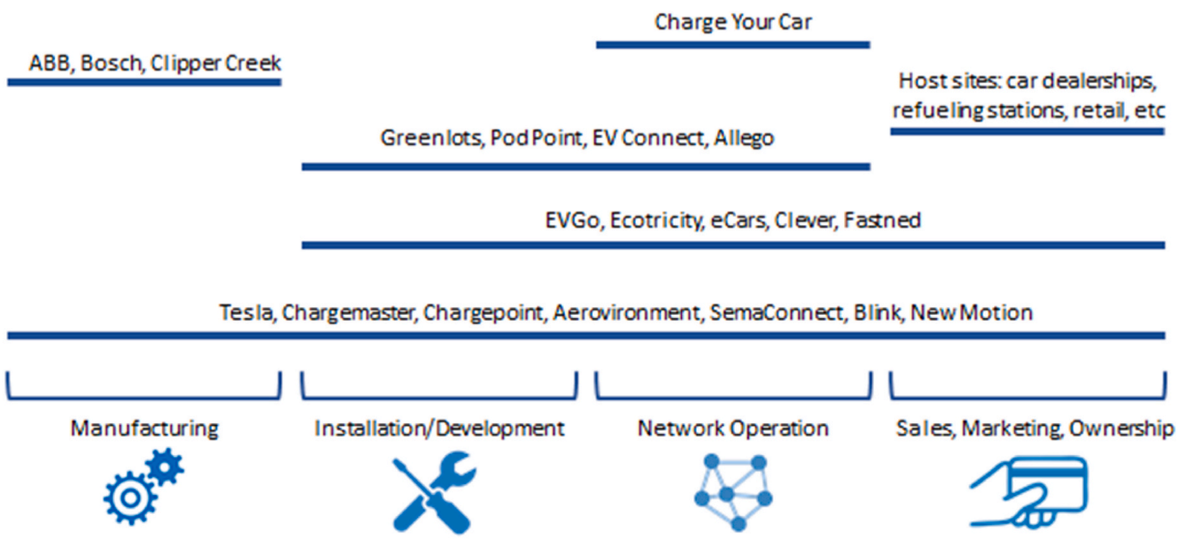

Fig. 2. Companies' activity in charging service functions*.

Bloomberg New Energy Finance (BNEF) [48] notes considerable consolidation among EV charging companies, as large energy firms acquire or invest heavily in infrastructure players, such as Royal Dutch Shell's purchase of Dutch charging company NewMotion, with its 20, 000 charging points, as well as Statoil's investment in Chargepoint, Engie's in EVBox, and Enel's in eMotorWerks. Given their institutional experience in building and maintaining electricity distribution networks, utilities are particularly well-suited for some aspects of the EV charging market. Power companies are responsible for 35% of all public charging stations in Germany [49], whilst in California, the electricity regulator recently approved $738 million of investment in transport electrification projects by three major utilities. Other US state regulators have approved or are considering similar utility proposals [50] (see Section 4 for additional discussion of utility ownership of EV charging infrastructure).[8]

In addition to electricity companies, large automakers are also playing an important role in building out charging infrastructure, through large joint partnerships [4]. For example, BMW, Daimler, Ford, and Volkswagen are members of the Ionity consortium, which offers an integrated European fast-charging network. The joint initiative was officially announced in November 2017 and has installed approximately half of its targeted 400 EV fast-charging stations across Europe, each with an average of six chargers per station [51]. Other similar consortia include Ultra-E, of which manufacturers Audi, BMW, and Renault are among the core partners, and the NEXT-E charging network, which involves participation from manufacturers Nissan and BMW, as well as Hungarian oil and gas company MOL and Germany utility E. ON. Car manufacturers Nissan and Tesla offer free charging access to customers who drive their vehicles [52]. Nissan provides US Leaf buyers or lessees an option to participate in a two-year free-charging programme, by which the driver receives a membership card valid for a range of public charging network providers; many Nissan dealerships also host charging infrastructure on-site [53]. While Nissan has taken a proactive approach to facilitating infrastructure buildout, Tesla has instead deployed its own proprietary fast-charging network for exclusive use of Tesla drivers, with locations in public-access areas that are near major highways in relevant markets [54]. In addition to its Supercharger network, Tesla also operates a Destination Charging programme, through which commercial entities may host Tesla charging facilities, which Tesla installs for free under certain conditions [55]. This approach is consistent with the model of vertical integration across all functions of the EVSE value chain. The proprietary characteristics of Tesla's network also raise challenges around market fragmentation and interoperability, limiting the degree to which Tesla infrastructure may contribute to a well-developed market for EV charging. As automakers continue to bolster their electric vehicle offerings, investments in charging infrastructure buildout would seem to be strategic, given the role that insufficient charging can play in deterring customers from EV uptake.

[8] This report includes subsequent discussion of the regulatory environment for utilities operating charging networks, however, comprehensive market data as to total utility sector investment in EV infrastructure is not readily accessible.

3.1.3. *Industry lessons learned*

The EV charging market holds some examples of approaches that have not been successful, which may be instructive in considering future models worthy of support. Garas et al. [27] cite a leasing model that was once employed by the Blink network, under which host sites entered into agreements to lease charging equipment from a supplier. The arrangement proved to be unpopular with prospective host entities because it required them to execute the installation and development function with respect to preparing sites for construction of charging facilities, which they were generally not equipped to do. Planning, zoning, and grid connection, for example, can be significant hurdles (and therefore represent considerable risks) to successful EVSE installation.

Another unsuccessful approach to EV charging infrastructure is the one taken by Better Place, an Israeli firm that shuttered in 2013. As mentioned in 3.1.1, the Better Place concept involved a model by which the company would retain ownership of the battery vehicle, with customers paying a mileage-based fee, and simultaneous development of a battery swapping and recharging network. Noel and Sovacool [56] examine the primary factors that led to Better Place's ultimate bankruptcy. They observe that a confluence of social, technical, political, and management considerations contributed to the failure of Better Place, but ultimately conclude that uptake of EVs in general was too poor in the key Better Place markets of Israel and Denmark to support the business.

3.2. *Economics of charging infrastructure*

The underlying cost drivers for electric vehicle charging involve a combination of upfront installation costs and ongoing operating costs. Evaluating these components can provide some indication of which subsegments of the EVSE value chain have the greatest potential to bring down overall costs.

3.2.1. *Upfront costs*

Upfront costs for EVSE include hardware (i.e. the actual charging station itself) as well as permitting, labour, and installation, which may involve considerable public works efforts. Depending on the site and the charging capacity of the planned infrastructure, upfront costs can also include connection and upgrades to the local distribution network. Non-hardware installation costs can also arise in the process of securing charging station access sites, such as parking spaces on public roads or in private parking areas. Smith and Castellano [57] discuss these factors in detail. Table 2, below, indicates estimated charging costs for both hardware and installation (inclusive of network upgrades) from a sample of available literature in both Europe, the US, Australia, and Asia.

The rapid development of EV charging technology introduces some challenges when attempting to classify the different types. In general, there typically had been AC chargers with Level One (<11 kW), Level Two (11 kW–22 kW) and Level Three (22 kW–44 kW) charging rates, along with the introduction of DC Fast (50 kW) chargers over the previous decade. However, the more recent introduction of DC Rapid (150 kW) and DC Ultra-Fast (350 kW) chargers radically shifts the scale [58]. These chargers are magnitudes quicker than the earlier AC chargers and cost several times more, however as DC Fast chargers have fallen in price it is expected that these will also. Chargers now range from the most basic 3 kW Level One AC chargers, that often come included with an EV purchase, all the way up to 350 kW behemoths that can charge an EV battery in minutes and which can cost several times the EV itself. In order to maintain a more manageable table, and due to limitations in the current research which regularly groups different, yet similar, speeds as one type, here we have decided on just three different types. Slow, medium-speed and fast chargers. Slow, or Level One, chargers are distinct in that they are overwhelmingly used overnight in the home, and because they are also considerably cheaper. Level Two, Level Three and DC Fast chargers now hold the middle ground with similar charging speeds and costs. DC Rapid and DC Ultra-Fast are an entity onto themselves, clearly becoming a third grouping with their high costs and extremely fast charging speeds.

As indicated, the cost of installing Level 1 charging for public access varies considerably, from installation of a new outlet in a commercial setting at €150 - €10,000. Both Level 2 and DCFC installations may require considerable public works and electrical upgrades, including strengthening local distribution networks, and can therefore require very high capital investments. Of course, specific site type and location, local regulations, and grid conditions can cause costs to vary widely, and economies of scale may reduce per-unit installation costs when installing multiple chargers at a single station. Nonetheless, high installation costs can make it difficult for a charging station to be profitable. Nigro and Frades [43] calculate the likely payback under cost assumptions at that time, and find that ownership of EV charging assets is not profitable under the current model, with a single DC fast charger resulting in developer losses of $44,000 over a 10-year period, and Level 2 charger with five connections resulting in losses of more than $26,000 over 10 years.

While these analyses provide some insight into charging station economics under a given set of assumptions, it is worth noting that higher utilisation rates will improve capital recovery timelines. In the meantime, the cost ranges presented in Table 2 indicate that installation and grid connection can comprise upwards of 80% of upfront EVSE costs. Policymakers could usefully consider approaches to streamlining planning and permitting processes, as well as mitigating network costs (e.g. by combining installation with other electrical works or identifying optimal locations for adding network assets).

3.2.2. Operating costs

Once installed, EV charging stations incur ongoing costs which include operations and maintenance services, as well as the purchase of electricity from a supplier or utility. The price of electricity and the structure of local electricity tariffs is a critical cost-driver for EV charging business models [75].[9] This is true for both residential and commercial installations in terms of the impact of electricity price structures on providing EV refuelling services.

The different residential retail rate structures can drive considerable variation in the costs of home charging. For example, a study commissioned by the New York State Energy Research and Development Authority (NYSERDA) in 2015 estimated that households charging electric vehicles at home could save up to $400 using a time-of-use rate, compared with the standard rate, depending on overall usage patterns [76].

For commercial charging station hosts, such as malls, supermarkets, and petrol stations, a tariff structure based on demand charges can limit the economic viability of charging.[10] For typical commercial consumers, these fees can make up a considerable portion of monthly electricity bills – sometimes 50% or more [77]. Given the high power rating of fast chargers, demand charges for EV charging companies and individual hosts offering 50 kW + charging capacity can be particularly acute. A comparison of an energy-only rate and a demand charge plus energy-only bill from a California utility found that an average cost of less than $5 per charge was realised with only 25 charges for the energy-only tariff, while the energy-plus-demand charge rate required 150 charges per month .[11] This is reflected in the savings to consumers [75]: found that EV customers could save from $1125 to $1220 per month or 58%–73% in total bills with critical peak pricing proposals.[12]

At present, the costs of charging infrastructure remain high, both in terms of the upfront installed cost, and potentially on an ongoing basis, depending on retail tariff structures. Though not discussed in detail here, utilisation rates can often be quite low: Helmus et al. [25]; reporting on Dutch public charging infrastructure, indicate 4–5 unique users per week charging for 40–60 h on average for each charger in recent years. Low utilisation rates, in turn, lead to poor cost recovery potential for many charging stations on an individual basis (portfolios of stations that include a mix of high- and low-utilisation chargers can help to ensure total costs are met).

3.2.3. Payment and fee structures

As identified in 3.2.1 and 3.2.2, charging service providers must cover the relatively high cost of hardware installation, particularly in the case of fast-charging facilities, as well as ongoing costs associated with maintenance and purchase of electricity for resale. Existing market participants commonly employ payment arrangements that are comprised of one or more fee types [78]. These typically include a fixed fee, such as an annual or monthly payment, a volumetric fee, under which customers pay for each kWh consumed, a time-based fee, under

[9] Electricity rates can also be structured to incentivize charging during off-peak electricity demand periods in order to manage grid operation impacts, as discussed in Section 4.3.

[10] Demand charges are calculated on the basis of the customer's maximum demand during a given time period, e.g. the highest 15- or 30-min increment of a year.

[11] The hypothetical charger in the analysis was rated at 50 kW and provided 20 KWh per charge. Results given here are for winter electricity rates [112]; present seasonal analysis but no detail on seasonal price differentiation. However, as California is a summer-peaking electricity market, seasonal electricity rates tend to be lower in winter and higher in summer.

[12] Critical peak pricing imposes a higher price for electricity used during peak hours throughout the year based on actual system outcomes, rather than a predefined time-of-use rate. In the case of proposed rates for SCE, a dynamic adder is charged to customers on a $/kWh basis for the top 150 h of system peak and top 200 h of circuit peak. estimated monthly utility bills using both existing and proposed tariff structures to charging station data in California charging stations operated by provider EVGo.

Table 2
Estimated EVSE unit and installation costs.

Source	Country	Level I		Level II/Level II/DC Fast		DC Rapid/DC Ultra-Fast	
		Hardware	Installation	Hardware	Installation	Hardware	Installation
Pillai et al., [59]; Indiamart [60],	India	₹70,000 -₹205,000 **(€807 - €2360)**	₹50,000 -₹120,000 **(€576 - €1383)**	Approx. ₹700,000 – (L.2 Only) **(Approx. €8065)**	Approx. ₹325,000 (L.2 Only) **(Approx. €3745)**	N/A	
Baik, Jin & Yoon [61],	Republic of Korea	₩3,150,000 - ₩6,300,000 **(€2248 - €4496)**	N/A	₩7,200,000 - ₩22,500,000 **(€5138 - €16,056)**	N/A	₩45,000,000 - ₩157,500,000) **(€32,112 - €112,391)**	N/A
Hove & Sandalow [46]; Qiao et al., [62] and Nelder, C. [63],	People's Republic of China	¥1200 - ¥1800 **(€149 - €223)**	Often Included with the Hardware Cost	¥25,000 - ¥35,000 **(€3095 - €4333)**	Approx. ¥15,000 **(Approx. €1857)**	¥350,000 - ¥2,000,000 - **(€43,334 - €247,621)**	
EVSE Australia Pty Ltd, [64]; EVSE Australia Pty Ltd, [65]; and ENERGEIA [66]	Australia	A$1000 - A $2500 **(€615 - €1539)**	A$800 - A$1800 **(€492 - €1108)**	A$2000- A $35,750 **(€1231 - €22,002)**	A$4000- A $15,000 **(€2462 - €9232)**	A$40,000 - A $100,000 **(€24,618 - €61,544)**	A$15,000 - A $60,000 **(€9232 - €36,926)**
Lee & Clark, [67]; Nelder & Rogers [68],	United States of America	Minimal		$2289 - $40,790 **(€1938 - €34,532)**		$112,709 - $224,590 **(€95,417 - €190,132)**	
Energy Saving Trust, [69]; Committee on Climate Change [70],	United Kingdom	£500 - £1000 **(€550 - €1100)**	N/A	£2000 - £40,000 **(€2200 - €43,973)**	N/A	£64,000 - £112,000 **(€70,357 - €123,125)**	
Tober, Bruckmüller & Fasthuber [71]	Austria	**€400 - €2750**	**€500 - €10,610**	**€1000 - €17,750**	**€4750 - €37,294**	**Approx. €60,000**	**Approx. €36,913**
Deloitte GmbH [72]; Auf der Maur, Brüggeshemke & KutscheraIm [73]	Germany	**Approx. €700**	**Approx. €2000**	**€2500 - €15,000**	**€5000 - €10,000**	**€62,500 - €81,250** (If Multiple Units Installed)	
Emobility Sweden [74], via IEA [7]	Sweden	$600 - $2100 **€507 - €1524**		$2300 - $64,000 **(€1947 - €54,182)**		Approx. $225,000 **Approx. €190,485**	

Note (1): Euro exchange rate taken as of 2pm, September 9, 2020.
Note (2): South Korea EV charger prices were estimated using a kW charge to price ratio as provided by Baik et al. this was then used against the most commonly sold EV chargers in South Korea to devise estimated price ranges.

which customers pay for the minutes or hours spent charging, and/or a per session fee, under which customers pay a flat fee to connect to a charger. Companies like US-based Chargepoint, which manages networked charging stations owned by individual charging station hosts, do not set pricing at a corporate level; pricing is established in these cases by the charging station owner. Others firms, like Irish utility ESB, provided charging at no cost initially, as the infrastructure had been funded through public support, but subsequently transitioned to membership and pay-*as*-you-go payment schemes. In Table 3 we provide an indicative survey of publicly available pricing information of 32 payment plans on offer from charging companies operating in various regions.

Of the 21 charging companies reported, approximately one third (7 companies) included a fixed fee. Approximately one half of plans included some form of a volumetric charge, one fifth included a time-based charge, and approximately 10% (2 companies, mainly DCFC) included a flat fee to connect. The remaining companies used some other form of fee structure, including free charging and charging rates set by individual station owners.

The diversity in payment schemes indicates that a single model for collecting revenues from charging is not yet clear or suitable for all markets but the trend is a shift away from flat fees to subscription and volumetric or time-based fees. Furthermore, in some cases, structures may reflect conditions specific to the regulatory framework in which companies are acting. For example, of the companies included in this sample, nearly all of the payment plans that were charged on a per-kWh rate were located in Europe. This may be due to a difference in regulation of electricity resale in European countries compared to US states. More broadly, the prevalence of the subscription model – present in a plurality of payment plans – is likely driven by the underdeveloped state of the EV market in general, meaning that low or sporadic utilisation rates require companies to use subscription fees to ensure steady revenues. Kley et al. [22] suggest that due to the high importance but low utilisation of public charging infrastructure under early market conditions, these assets could be more appropriately funded from home-charging as a core business. However, as EV ownership becomes more widespread and public charging volumes increase, it is likely that payment plans will continue to evolve. From a consumer protection perspective, a standard method for refuelling costs is critical, as the range of different rates and billing types leads to poor transparency and comparability for customers.

Charging services are also offered as part of emerging sharing-economy business models, as in the case of EV drivers who own home charging infrastructure to make their equipment available for public use, either for free or for a usage fee [52].[13] In some cases, this has been executed as a dedicated platform, as with Swedish ElBnB, launched by Renault in 2016, which allows drivers to locate and contact a charging station owner [79], as well as Chargie, in the UK which uses a similar model [80]. Another approach leverages existing sharing-economy platforms to establish partnerships between current market actors, as with Airbnb and Tesla [81].[14] While beyond the scope of this paper, it should also be noted that charging network operators – both residential and public charging companies – may develop storage aggregation for demand response and flexibility services under vehicle-to-grid arrangements, which could provide additional revenue streams.

[13] This is true for standalone homes or those with access to dedicated parking and associated EVSE; multi-unit buildings do not generally offer drivers the same opportunities to own chargers and participate in the business models described here.

[14] These examples generally refer to charging at single-family homes, rather than multi-unit buildings, where charging costs may be allocated across multiple tenants.

Table 3
Representative list of charging companies and fee structures.

Company[1]	Country	Fee Structure
Chargefox	AU	Pricing rate and structure set by station owner, typically AU$0.40 per kWh
Blue Corner	BE	Volumetric Fee - €0.40/kWh AC; €0.69/kWh DC Annual Fee + Volumetric Fee - €59/year; €0.35/kWh AC; €0.60/kWh DC Annual Fee + Volumetric Fee - €169/year; €0.33/kWh AC; €0.56/kWh DC Pay by Minute - €0.01/min AC; €0.25/min DC
Tgood	CN	RMB 0.45/kWh to RMB 2.36/kWh[2]
StarCharge	CN	RMB 0.45/kWh to RMB 2.36/kWh[2]
State Grid	CN	RMB 0.45/kWh to RMB 2.36/kWh[2]
Wanbang NE	CN	RMB 0.45/kWh to RMB 2.36/kWh[2]
Innogy	DE	Volumetric Fee - €0.39/kWh and €7.95 for DC Fast charging.
Fastned	DE/NL	Volumetric Fee - €0.59/kWh Monthly Fee + Volumetric Fee - €11.69/month + €0.34/kWh
Clever	DK	Volumetric Fee – 295 DKK (~€40) to 799 DKK (~€105) depending on the subscription type.
IZIVIA	FR	Monthly subscription of €10-€30, charging rates of €.50 - €1 per 5 min.
ESB eCars	IE	Monthly fee + Volumetric fee - €4.60/month + €0.23/kWh Volumetric fee only - €0.27 per kWh
KEPCO	ROK	KRW ₩52.5/kWh up to KRW ₩232.5/kWh depending on season.
ChargePoint	Several	Pricing rate and structure set by station owner
Tesla	Several	Ireland - € 0.29 per kWh United Kingdom - £ 0.24 per kWh Germany - € 0.33 per kWh USA - $ 0.28 per kWh
BP Chargemaster	UK	Monthly Fee + Volumetric Fee - £7.85/month + £0.12/kWh (most chargers included in the monthly fee)
ChargeYourCar	UK	Pricing rate and structure set by station owner
Ecotricity	UK	Volumetric Fee - £0.30/kWh and £0.15/kWh for members (bundled with home electricity)
AeroVironment	USA	Monthly Fee - $19.99/month Sign-up Fee - $15 Pay by Session - $4 (L2) or $7.50 (L3)
Blink	USA	- States that permit kWh pricing - $0.39 to $0.79 per kWh (L2) or $0.49 to $0.69 (USD) (DCFC) - States that do not permit kWh pricing - $0.02 to $0.03 (L2) per 30 s or $6.99 to $9.99 (DCFC) per session
EVgo	USA	Monthly Fee + Pay by Minute - $7.99 + approx. $0.28/min (DC) Monthly Fee + Pay by Hour - $7.99 monthly fee + $1.50/hour (L2) Pay by Hour - $1.50/hr (L2) Minute DC charging rates vary by US state.
SemaConnect	USA	Pricing rate and structure set by station owner

Notes.
[1] Website details for each charging scheme are provided in Appendix 1.
[2] The Chinese EV charging market is highly regulated, prices are capped but research suggests the stated range [46].
Source: own analysis

4. Incentives and deployment approaches

From the discussion so far, it is clear that EV charging infrastructure can be privately or publicly financed and funded. This section therefore addresses the issues (i) who should finance and fund charging infrastructure, i.e. the funding roles; (ii) what instruments should be used to support EV charging infrastructure investment, and (iii) the impacts of EV charging infrastructure on the electricity network.

4.1. *Funding roles in EV charging infrastructure*

EV charging infrastructure shows certain public good characteristics common to public infrastructure and in the early years of EV deployment merits some public financial support [82].[15] EV experts interviewed in the Kester et al. [21] study agreed that the business case for privately-operated charging stations still doesn't make sense. Because the likely social benefits are not limited to those who can pay, decisions about this infrastructure are an important public policy concern and should not be just a matter for private firms and investors; it is therefore rarely fully privately-funded or owned [83]. In addition, publicly-owned electricity generation and transmission utilities often own and/or finance EV charging stations, which makes them a matter for public interest. Public funding can be raised from the general tax base or from charges to electricity ratepayers, with implications for the distribution of the cost of supporting public infrastructure.

Fitzgerland and Nelder [84] note the need for public investment particularly in fast-charging infrastructure, which requires an adequate supply of "patient capital" to support high upfront expenditures that may not be returned to investors for several years, as EV usage grows and boosts revenues. They also point out that even with respect to Level II charging, allowing for public investment either through charges to ratepayers or general taxation is necessary for the early deployment of infrastructure. While in the short-term this may represent cross-subsidization of wealthy early-adopters, in the long-term, robust EV use will be profitable and beneficial to a broad cross-section of society, not only EV drivers.

The role of utilities or incumbent energy suppliers in providing public charging infrastructure varies widely around the world and is the subject of great debate. Monopolistic development (by private or public entities) of future infrastructure such as EV charging could raise prices and prevent future competition, particularly where the supplier is also the electricity retailer. Yet at early stages of EV adoption, where profits from charging stations are low, other private actors may not have the capacity or resources to invest. In Europe, large energy companies have been responsible for a significant proportion of all public charging stations—for example, energy supplier RWE owned more than 2800 charging stations across Germany and other countries in 2017 [4].

Opening up utility ownership of EV charging infrastructure through regulatory policy has also been used in some US states, such as Washington, California, and Missouri, in order to promote deployment. Regulators have in some cases reversed earlier policies that prevented investor-owned utilities from investing in installation of EV charging infrastructure and passing the corresponding costs on to ratepayers [85]. For example, in 2015, Kansas City Power and Light (KCP&L) became one of the first US utilities to launch a public charging network, and in 2016 was third among fifty US cities in charging infrastructure availability and the city has since doubled EV deployment [14,84]. Outside of the US, Tokyo also allows for utility ownership of EV supply equipment, and the Netherlands has created an auction system for all public charging station installations, in which utilities can bid competitively for funding to provide charging access [4]. In Ireland, the regulated DSO, ESB Networks, was authorised to spend €25 million from ratepayer network user fees to build a national public charging network, though regulators have recently indicated a preference for transitioning to a competitive marketplace for charging services [86].

Hall & Lutsey [87] note in their review of best practice that utilities using ratepayer funding (or "rate-basing") to support EV charging can have varying implications for competition. Access to ratepayer funds can allow utilities to absorb early-stage losses, potentially enabling them to crowd out private actors. However, heavy utility regulation could also inhibit innovation and agility, putting utilities at a disadvantage compared to private companies. In either case, the paper notes that where utilities do own charging infrastructure, it may be beneficial for governments to promote public-private partnerships, and to target utility-led development to specific market segments that may be

[15] For example, the deployment of EVs is a key element of strategies to decarbonise transport and mitigate climate change to the benefit of society.

underserved by the private market, like apartment buildings and workplace charging.

Rate-basing the costs of installing and operating EV charging infrastructure is permitted in some jurisdictions if utilities are able to make a "compelling" case that rate-based expenditures on charging stations would provide a net benefit to all their customers (see for example the Oregon Public Utilities Commission) [88].[16] Alternatively, public funds could be raised through general taxation; yet as with all taxation measures, there are potential distortionary effects associated with increasing taxes.

Whether funded directly by utilities or by private actors such as charging companies and automakers, Kalani [89] notes that EV charging, and particularly fast-charging, should be regulated in a manner similar to that applied in electricity delivery. Under typical utility regulation in telecommunications and electricity, ownership of wires should be separate from the electricity they carry, ensuring access to infrastructure for users while allowing for competition in supply. Kalani [89] points to these outcomes – ease of access and competitive markets – as necessary for keeping the overall cost to society for EV infrastructure as low as plausible. This also allows for interoperability, such as exists in mobile phone networks. The success of charging infrastructure will be linked to the number of users it can attract. For example, clear agreements in the telecommunications sector in network sharing and separation of sales volume (e.g. for mobile data and electricity) has led to benefits for all.

Rules governing retail sales of electricity can act as a barrier for current and prospective charging service providers. Fitzgerald and Nelder [84] note that some jurisdictions allow EV charging station operators to sell electricity directly to customers, whereas in other locations, only entities which are regulated as utilities may participate in the resale of electricity. A lack of certainty around these regulations can inhibit commercial charging operations entirely or can impact payment structures, as in some locations where companies charge for access to a parking space, but do not charge for electricity on a per-kWh basis. For example, in 2017 the state of Indiana changed its regulatory conditions to allow for resale of electricity for EV charging as long as customers were not paying a per-unit price [90]. In the UK, full resale of electricity through commercial charging infrastructure is permitted, and a 2014 decision from Ofgem waived the maximum retail price allowable for suppliers in the case of EV charging [91]. In summary, while EV ownership is low and there is little or no profitability in the installation and operation of charging stations, public funding is required. In the long run with greater EV uptake, a transition to commercial operation is possible and desirable.

4.2. Instruments to support investment in EV charging infrastructure

A range of supportive policy measures at local, regional, and national levels of government can be used to bolster public EV charging networks. The IEA notes that effective policy frameworks create conditions to overcome key barriers to developing EVSE [2]. This is achieved through a combination of measures, including the definition of clear EVSE deployment targets, supportive regulations, mobilisation of funding for direct investment and the provision of financial support.

Designing incentive schemes that promote development of charging requires policymakers to consider several factors: how and from whom funding should be collected as discussed in the previous subsection, how and to whom funding should be allocated, and how to plan for future impacts that arise from widespread deployment. The choice of scheme will depend on all the above factors. Policy measures to support EV charging can be implemented in the form of ad-hoc programmes that provide incentives to individual EV owners or EVSE providers, or through more comprehensive investments in network development, or centralised network development tenders with implications for efficacy and equity for prospective recipients.

At the local level, municipalities can provide incentives and support such as efficient processing of charging station siting applications or allocation of parking spaces exclusively for electric vehicles or charging activity. The city of Paris provides dedicated free parking spots for EVs, while Amsterdam uses a demand-based approach to deploy public access charging by installing chargers at the request of residents who purchase EVs when there is no private or off-street alternative nearby [49]. More broadly, the UK's national programme for support of local authorities' on-street charging infrastructure deployment requires applicants to demonstrate a lack of off-street parking access [92].[17] These approaches optimise utilisation by ensuring that public funding for chargers is aligned with the demand for charging services [93]. A rollout strategy that targets high utilisation rates can also be beneficial in enabling charging assets to maximize revenues, supporting a profitable business case for deploying them [84].

Regional and national governments can address public charging deployment through policy interventions that address the high-need, low-use market characteristics of charging infrastructure.[18] This can be done either through direct investment in public-private partnerships to build out networks, or by offering grants and other incentives to make development attractive to private companies. One example of a public-private partnership for charging infrastructure is the West Coast Electric Highway, a network of Level 2 and DC fast-charging stations (50 kW) located every 25–50 miles along major roads in Oregon, California, and Washington state [94]. The West Coast Electric Highway project received support from the three states in which it is located, as well as federal funding from the American Recovery and Reinvestment Act, as well as the Department of Transportation [95]. Private entities, namely the host sites at petrol stations and rest stops along the network route, contribute to the network by developing, installing, and operating the chargers [96]. Another example of public-private partnership is Fastned, which operates a network of fast-charging stations in the Netherlands, and has agreements in place to expand to Germany and the UK. The network is raising funds for future buildout through a public bond offering, in which bonds are offered at 6% interest with a maturity of five years [97].

The state of Connecticut, rather than investing directly in development of a network, launched an initiative in 2013 that offers grants to both public and private entities who install Level 2 charging equipment. A key provision of allocation of this funding is that recipients must ensure that supported charging infrastructure is available for public use (i.e. that it is not limited for use only by a hotel's guests or a restaurant's customers, for example). In addition, the state has worked with a local utility to roll out DC fast-charging, and by choosing to co-locate fast-chargers with planned Tesla Motors charging stations, was able to reduce costs during the construction period of the network [95]. Similarly, the Norwegian government, via state agency Enova, introduced a support scheme in 2015 meant to deploy DC fast charging stations every 50 km around a 7500 km road network. Under the scheme, network operators retained ownership and operational responsibility for charging assets, and competed for public funding to support deployment [98].[19]

[16] Public Utility Commission of Oregon. 2012. Order No. 12,013. Investigation of Matters Related to Electric Vehicle Charging. http://apps.puc.state.or.us/orders/2012ords/12-013.pdf.

[17] [8] note that Amsterdam's programme has proven more successful than London's, where the budget was not fully depleted due to a complicated approval process.

[18] In the EU, the directive 2014/94/EU on the deployment of alternative fuels infrastructure recommends a fast charger every 50 km for example.

[19] As an aside, the last two tenders of this project have yet to be completed, as no companies bid to build a charger in the very north or the Lofoten islands, even with 100% subsidy on the equipment.

Irrespective of the type of public support provided for charging networks, incentive initiatives should be clear about any ownership stake or encumbrance implicit in accepting government support. For example in Ireland, following a DSO-led pilot project to roll out charging stations across the country using ratepayers funds, the regulator issued a decision stating that the DSO could no longer use ratepayer funds to install further stations and that assets should be sold off.[20] Though the decision has since been replaced by an interim agreement for the ownership and operation of the network, the initial ruling led to some uncertainty regarding the future expansion of charging infrastructure and the management of the current asset. Such ambiguity can lead to underinvestment in network maintenance, resulting in long outages and general disrepair, which in turn can fuel hesitation among potential EV buyers.

The recast EU directive on common rules for the internal market for electricity states that DSOs may not own, develop, manage or operate charging infrastructure except under certain conditions [99].[21] Such conditions will be relevant to the future value of charging networks as prospective investors become more familiar with the EV charging model. If the infrastructure is initially publicly owned, arrangements will be needed if there is to be a transition to private ownership. For example, Dougherty and Nigro [100] note that financial actors could play an important role in creating a secondary market in which existing infrastructure assets could be packaged as securities and sold to investors.

Ensuring clarity in asset ownership for infrastructure financed by governments or ratepayers should reduce the cost of such transactions, bringing down overall cost of capital and helping to mobilise private capital to leverage public investments.

4.3. Network impacts of EV charging

In considering the need for public and/or private funding of charging infrastructure, network investment may also need to be added to the overall system costs. The prospective uptake of electric vehicles at scale will precipitate a need for changes and upgrades to physical electricity networks to accommodate localized peaks and also, less significantly, an increase in demand for electricity [101]. Rabiee et al. (2021) model the interaction of EV and PV operation and show how it can be optimised to reduce constraints at the distribution and transmission levels. Managing electricity demand from EVs can reduce the need for future network investment by providing storage and other grid services. As such, charging network planning should consider both where and when changes in demand may occur, taking account of spatial planning and potential for network hotspots, as well as charging behaviour and temporal incidence of charging events.

Separate from fiscal deployment strategies discussed in Section 4.2, residential charging may also be bolstered by national or supernational policy. In Europe, for example, the EU Commission has proposed amending energy performance standards, or building energy codes, to require new residential buildings, as well as those undergoing major renovations, with more than ten parking spaces to be wired for vehicle recharging, beginning in 2025 [102]. In jurisdictions with such requirements, network operators could engage with development planning processes to track and forecast future charging demand.

Practical utilisation of networks and behavioural charging patterns will have significant implications for how charging interacts with electricity infrastructure. Fitzgerald and Nelder [75] analyse charging events in the EVGo network in California and find that the utilisation profile for chargers at all types of charging host sites follows the same pattern as overall system demand. This suggests that use of public fast-charging at wide scale could have the effect of exacerbating demand peaks, resulting in added costs for network operation and capacity. They also notes the potential to use recycled electric vehicle batteries to mitigate peak demand from charging stations, allowing for further reductions in both demand charges and network costs.

Richardson [103] provides a comprehensive review of literature on potential grid impacts of EV charging and notes the importance of smart or responsive charging infrastructure in avoiding an increase in network costs. Retail tariff price structure can also be employed to manage the timing of demand. For example, EV owners in San Diego in 2013 (which had, at the time, a fleet of 3300 EVs and 400 public charging stations) could avail of a time-of-use (TOU) tariff for separately-metered EV charging. These tariffs are credited with encouraging the high proportion of EV charging – more than 80% – which occurs between midnight and 5:00 a.m. [104].

There have been several studies investigating the potential for EV charging to provide demand response and avoid network upgrades. One demonstration of responsive charging at residential scale in includes the “My Electric Avenue” project in the UK. They concluded that utilisation of demand response for EV charging to avoid network upgrades in Great Britain could yield savings of approximately £2.2bn by 2050 [105].

5. Conclusions and policy recommendations

EV charging infrastructure is a critical enabler of the deployment of EVs. This review has sought to highlight key considerations for policy makers and stakeholder in its rollout in terms of private actors, business model, and regulation. We draw several conclusions and insights from this review into the ways in which charging services are used and delivered, and which measures can promote their deployment.

Greater transparency is needed for customers to be fully informed about the costs they face when using commercial charging services. The variety of charging service pricing structures – e.g. through per-minute, per-hour, per-kWh, or through subscription services – obscures the comparative price of charging between operators and home charging. Improving consumer protection legislation or introducing standardized labelling could help to improve the customer experience when searching out charging services.

Charging infrastructure remains expensive to install and maintain. The full social benefits of electric vehicle usage are not captured in the price signals that consumers face with respect to private vehicle usage. Charging infrastructure in many geographies therefore requires continued support through various publicly-funded subsidies and public-private partnerships. Ways in which public authorities can support charging services efficiently include targeted demand-driven buildout programs and strengthened building regulations to encourage installation of chargers in new and renovated residential buildings. Policies governing utility ownership of EV charging infrastructure need to balance the importance of leveraging the institutional capability of electricity companies to build and maintain networks with the need to ensure that markets are efficient and competitive.

Finally, data on public charger usage is notoriously difficult to obtain. Private actors could be required to make more data publicly

[20] Commission for the Regulation of Utilities [86] ESBN Electric Vehicle Pilot and Associated Assets, Decision paper CRU17283.

[21] ‘Member States may allow distribution system operators to own, develop, manage or operate recharging points for electric vehicles, provided that all of the following conditions are fulfilled: (a) other parties, following an open, transparent and non-discriminatory tendering procedure that is subject to review and approval by the regulatory authority, have not been awarded a right to own, develop, manage or operate recharging points for electric vehicles, or could not deliver those services at a reasonable cost and in a timely manner; (b) the regulatory authority has carried out an ex ante review of the conditions of the tendering procedure under point (a) and has granted its approval; (c) the distribution system operator operates the recharging points on the basis of third-party access in accordance with Article 6 and does not discriminate between system users or classes of system users, and in particular in favour of its related undertakings. The regulatory authority may draw up guidelines or procurement clauses to help distribution system operators ensure a fair tendering procedure.’

available, while protecting customers' data and confidential commercial information. More easily accessible data would allow the research community and policymakers to conduct valuable analysis around usage of the existing network, and to better evaluate attitudes and behaviours for current and prospective EV drivers. Beyond infrastructure usage, a broader transportation survey effort could capture which driving and refuelling habits, commuting modes, travel distances, and other driver characteristics which would be essential to establishing detailed driver profiles. Such information would provide critical insight into planning and siting future assets by eliciting drivers' needs and preferences for where and when they wish to charge.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[113,114].

Acknowledgements

This work has emanated from research conducted with the financial support of the Department of Environment, Climate and Communications (DECC) under the EMPowER project and Science Foundation Ireland under the SFI Strategic Partnership Programme Grant Number SFI/15/SPP/E3125. The authors are grateful to Andrew Kelly (Envecon) and Sacha Schieffer (International Energy Agency) for their review of the paper, as well as to ESB eCars, the Sustainable Energy Authority of Ireland, the Society of the Irish Motoring Industry, and many other stakeholders for sharing data, insight, and experience. We also appreciated helpful comments from the IEA HEV Task 1 Meeting in Dublin in April 2018, and the DCCAE Low Emissions Vehicle (LEV) Task Force.

Appendix A. Links to charging company websites

AeroVironment

https://chargehub.com/en/networks/aerovironment.html.

Blink

https://blinkcharging.com/drivers/pricing/(They removed their DC charging rates).

https://chargehub.com/en/networks/blink.html (Could be an older link, it's undated).

Blue Corner

https://www.bluecorner.be/fr/abonnements-et-cartes-de-recharge/

BP Chargemaster

https://bpchargemaster.com/

ChargePoint

https://na.chargepoint.com/faqs#F10.

ChargeYourCar

https://www.chargeyourcar.org.uk/

Chargefox

https://www.chargefox.com/ev-facts/
https://www.chargefox.com/retail/

Clever

https://clever.dk/produkter/abonnementer/clever-all-in-one/

Ecotricity

https://www.ecotricity.co.uk/

ESB eCars

https://www.esb.ie/ecars/news/2020/2020/07/08/esb-ecars-introduce-pricing-on-the-standardchargers-to-support-continued-ev-network-expansion.

EVgo

https://www.evgo.com/charging-plans/

Fastned
https://support.fastned.nl/hc/en-gb/articles/205420047-What-are-the-costs-for-charging-
Innogy

https://iam.innogy.com/fuer-zuhause/elektromobilitaet/autostromtarife.

IZIVIA

https://www.izivia.com/en.

KEPCO

https://home.kepco.co.kr/kepco/EN/F/htmlView/ENFBHP00102.do?menuCd=EN060201.

SemaConnect

https://semaconnect.com/resources/faq/

Tesla

https://teslanomics.co/tesla-supercharger-rate-calculator/
https://www.tesla.com/en_IE/support/supercharging
https://www.tesla.com/support/supercharging#locating-supercharger.

Credit author statement

Sarah La Monaca: Data curation, Methodology, Investigation, Writing- original draft, review and editing. Lisa Ryan: Funding acquisition, Methodology, Project administration, Supervision, Writing – review, revisions, and editing.

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