# Electric Vehicles Rollout—Two Case Studies

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**ABSTRACT**

***We present and discuss evidence on electric-vehicle rollout in The Netherlands and Norway, two forerunners in this area. We demonstrate that the uptake of electric vehicles is essentially driven by financial and other benefits offered to their owners, and that a partial electrification of the vehicle fleet may be achieved even with limited public charging infrastructure; indeed, infrastructure has tended to follow the development of electric vehicles. The impact on the electricity industry in general and electricity networks in particular has so far been limited, even given the relatively high penetration of electric vehicles.***

**Keywords:** Electric vehicles, Charging infrastructure, Electricity networks

https://doi.org/10.5547/2160-5890.10.2.fbal

## 1. INTRODUCTION

There is much speculation about the rollout and impact of electric vehicles, but so far there is little experience due to the fact that, in most countries, their penetration is limited. We present two cases where electric vehicles are sufficiently important for some lessons to be drawn on the consequences for energy systems and markets.

Backed by an attractive subsidy scheme, Norway leads the way in electric-vehicle sales, with a 55.9 per cent share of new registrations in 2019 (IEA, 2020). Norway was also the leader in terms of share of electric vehicles in the total stock, with a 12 per cent share. The Netherlands has seen fluctuations in the market share of electric vehicles due to changes to its subsidy scheme, but it is now at 15.1 per cent; the stock share is 2.5 per cent. Development of the total number of battery (BEV) and plug-in hybrid electric vehicles (PHEV) per thousand capita is given in Figure 1.

We first consider drivers for the uptake of electric vehicles. Given that all countries have access to the same car models and technologies, yet the speed of adoption differs, local factors must be very important. We look at a number of such factors, including incentive schemes—taxes and subsidies—development of charging infrastructure and urban development features.

We next study how electric vehicles are used. Do they fully replace traditional cars or are they mostly supplementary? Who is likely to buy an electric vehicle and for what needs? Are there specific geographical patterns in the adoption of electric vehicles?

Finally, we consider the impact of electric vehicles on the power system. The relative increase in electric energy demand, and the associated impact on the grid and the overall power system, will depend on a number of factors. These include the size of the electricity system,

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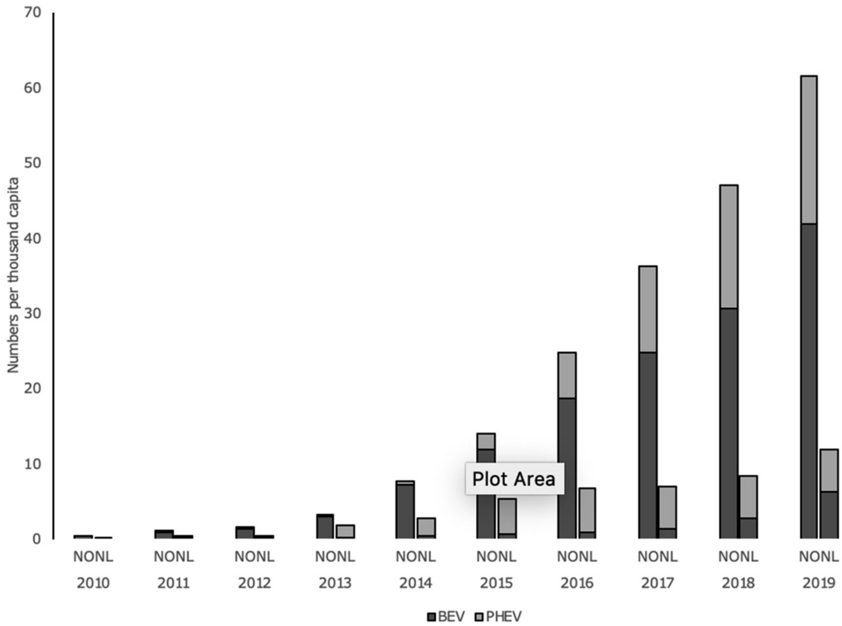
**FIGURE 1**
Number of BEV and PHEV per thousand capita.




Source: EAFO (2020), Eurostat, authors' calculations.

charging behaviour—for example where and when charging takes place—the current state of the electricity infrastructure as well as the ability of the system to respond to increased demand.

The structure of the paper is as follows: the next two sections present case studies of Norway and the Netherlands. In the penultimate section we discuss lessons learned from these cases and in the concluding section suggest their wider application.

## 2. NORWAY

The Norwegian government has an unusually ambitious policy to promote electric vehicles, providing a combination of tax exemptions and benefits that make them very attractive. A number of local governments—especially in major cities—have developed their own policies with regard to electrification of the transport sector. Policies—which in Norway have been more or less stable since their first introduction—are summarised in Table 1.

From an economic point of view, the most important policies are the fiscal incentives associated with exemptions from registration and value added taxes (VAT) (Fridstrøm and Østli, 2017). These policies reduce the price of a battery electric vehicle by between a fifth and a half (Bjerkan, Nørbech and Nordtømme, 2016). High taxes on fossil fuels, in combination with relatively low electricity prices, provide further economic incentives (Figenbaum and Kolbenstvedt, 2015). As a result, battery electric vehicles are competitive when compared with corresponding vehicles running on traditional fuels (Figenbaum, 2018); indeed, as shown in Figure 3, the cost of ownership for the most popular electric models relative to that of corresponding conventional models is approximately halved.

Based on survey data, Figenbaum and Kolbenstvedt (2016) estimate the value of local incentives for the average electric-vehicle owner to be €1,500 per year, of which toll roads

**TABLE 1**
Policy instruments with date of first introduction.

| | Norway | The Netherlands |
|---|---|---|
| **Purchase** | Registration tax, 1990<br>VAT, 2001 | Registration tax, 2010<br>Local purchase subsidies, 2013<br>Investment tax deduction, 2017 |
| **Usage** | Annual vehicle fee, 1996<br>Company car tax, 2000<br>Re-registration tax, 2018<br>Toll roads, 1997<br>Ferry rates, 2009<br>Parking fees, 1999<br>Access to bus lanes, 2003 | Annual vehicle fee, 2011<br>Tax on private use of company cars, 2011 |
| **Infrastructure** | Financial support for charging stations, 2009 | Financial support for charging stations, 2010 |

accounted for 50 per cent, time savings in bus lanes for about 30 per cent, free parking for another 16 per cent and ferry rates for about 4 per cent. Around 10 per cent of respondents claimed to receive no benefits from these incentives, whereas a similarly sized group valued the benefits at more than €5,000 per year. The higher values were found around the largest cities, providing a plausible explanation for why take-up rates of electric vehicles have been particularly high there.

There is no specific regulation or public support for installations of chargers in private homes in Norway (Figenbaum, 2018). There are, however, a number of local-authority programmes to support chargers in apartment buildings. The government recently introduced regulation stating that, in co-owned housing facilities, owners may require that charging stations be put in place.

The government has had support programs for fast-charging stations since 2011 (Figenbaum, 2018). In the beginning, there were no restrictions on the geographical placing of charging stations. This policy has gradually evolved due to the development of deployment strategies, now mainly aimed at ensuring sufficient coverage on all main routes. Several rounds of public tenders have resulted in a basic network of chargers every 50 km along all major transport corridors. However, a considerable number of charging stations have been set up without any public support, especially in cities (where such support is not available).

Charging stations are connected to the electricity grid at the distribution level. Network owners are obliged to accept requests for connection of charging stations on the same terms as those offered to commercial (or non-household) users. Users are required to cover all connection costs, including upgrades of the network that are triggered by the connection. The so-called "anleggsbidrag" (investment contribution) allows the network company to impose on a user the actual cost of a new or upgraded connection. There is no regulation concerning where charging stations may be placed, but the economic incentives arising from connection charges encourage placing them where the resulting network costs are relatively small.

Bjerkan, Nørbech and Nordtømme (2016) suggest that charging infrastructure has a lower importance for purchase decisions than other incentives. Figenbaum and Kolbenstvedt (2016) report that the availability and quality of charging infrastructure appears to be only a small problem: 83 per cent of the respondents in their study never had to avoid a trip due to in-sufficient charging infrastructure or because the range of the vehicle was too short. It should be noted that these results are based on surveys among owners of electric vehicles. Thus, the possibility exists that lack of access to infrastructure prevented purchase of an electric vehicle in some cases.

Norway is probably one of the countries in Europe where establishing a basic charging infrastructure for electric vehicles is least challenging (Figenbaum, 2018). 75 per cent of all households can park a vehicle directly on their own land, and a further 12-13 per cent can park in their own parking space less than 100 meters from home. Most households in Norway rely on electricity for space heating and with 10A or 16A connections have sufficient capacity to handle a 2-3 kW electric-vehicle charger. Newer houses with a 32A or 64A three-phase connection can handle a 7-11 kW charger.

Home charging in apartment buildings and other types of houses where parking is in shared facilities has proved more difficult (Figenbaum, 2018). By the beginning of 2018, electric vehicle chargers were installed in only 18 per cent of housing cooperatives and condominiums. Neighbourhood on-street home-charging is even less common and very few electric-vehicle owners rely on such charging solutions (Figenbaum and Kolbenstvedt, 2016).

Many employers offer charging at the workplace. According to Figenbaum and Kolbenstvedt (2016), 28 per cent of electric-vehicle owners use such charging facilities on a daily basis and a further 10 per cent on a weekly basis (see also below).

Electric-vehicle charging stations have been built rapidly over recent years, cf. Figure 4 below. Charging stations are built and operated by both public authorities (mostly municipalities) and private companies including electricity retailers. Stations typically offer a range of chargers (normal, CHAdeMO and CCS), different payment schemes and various payment methods, including via SMS and freely available apps, often with rebate schemes.

Electric vehicles tend to be driven as much as vehicles running on conventional fuels. In 2017, diesel vehicles were on average driven 15,100 km and petrol vehicles 9,100 km, while electric vehicles were driven 11,800 km over the year. Figenbaum (2018) argues that electric vehicles are typically used for local transport, often as the “secondary” vehicle in multi-vehicle households. By studying toll road data, he presents evidence supporting the view that electric vehicles are mostly used locally. These results are reinforced by survey evidence, showing that electric vehicles are used more frequently than conventional vehicles for commuting, as well as for local visits, shopping and leisure and when transporting children, but less for vacations and longer trips (Figenbaum and Kolbenstvedt, 2016).

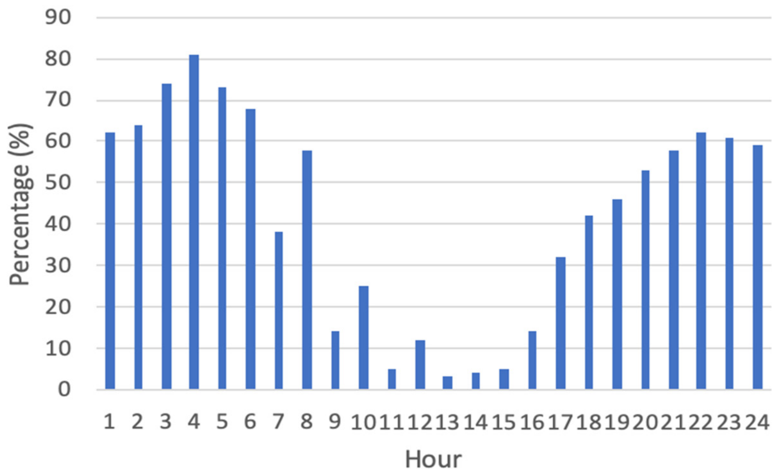
According to Figenbaum and Kolbenstvedt (2016), 79 per cent of electric-vehicle owners have more than one vehicle at their disposal; the additional vehicles are typically conventionally fuelled. For comparison, in 2018 only 26 per cent of all households which owned a vehicle possessed more than one vehicle (Fjørtoft and Pilskog, 2019). Moreover, ownership of electric vehicles is concentrated among the well-off: 16 per cent of households in the highest income quartile owned an electric vehicle, compared to 0.6 per cent in the lowest income quartile and an overall average of 6 per cent. A stylised portrait of the early pioneers is thus that they are people who have access to private charging and can afford a second car for local transport.

The usage pattern may go a long way in explaining why charging of electric vehicles mostly occurs at home. Sæle and Petersen (2018) found that 59 per cent of respondents living in single-family houses, row houses or similar accommodations charge at home on a daily basis, while 25 per cent do so on a weekly basis. The numbers are considerably lower for respondents living in housing cooperatives (78% of these never charge at home), presumably because access to charging is more difficult there. Charging at fast and public charging stations is done less frequently, with more than 80 per cent of the respondents doing so only monthly or less often; such charging—which tends to be about four times as costly as home charging—mostly takes place on longer trips (Figenbaum, 2018). Half of the respondents charge at work, but only 17 per cent on a daily basis.

Sæle and Petersen also found that home charging tends to take place in the evening and at night. Figure 1 gives the fraction of respondents charging at home at a given time of the day. It shows that 60 per cent or more charge in the late evening or at night and only very few during typical office hours.[1] A considerable number of respondents charge their vehicles during hours when total electricity demand is peaking, i.e. in the morning, afternoon and early evening.

**FIGURE 2**

Fraction of respondents surveyed charging at home in respective hours.




Source: Sæle and Petersen (2018).

These results conform with profiles based on actual measurement of a group of home chargers (Skotland, Eggum and Spilde, 2016). This measurement shows that the average home charging power consumed by an electric-vehicle owner on any given day is very low—around 150W over all 24 hours, with a peak of 250W during night. This is due to the fact that charging of vehicles does not take place every day.

The charging pattern at fast-charging stations is very different, with a peak around 17.00 (Skotland, Eggum and Spilde, 2016). There is little difference in the use of fast chargers between weekdays and weekends and between seasons. Charging at work starts around 6.00, increases steadily until 9.00 and then gradually falls off until the end of the workday.

Until now, it would seem that electric vehicles have presented only minor challenges to the electricity grid. Overall, the charging of electric vehicles in Norway has only added a small fraction to the overall electricity demand (less than 1 per cent measured in energy) and hence has only minor effects in the aggregate, i.e. at the regional and transmission levels of the network. Furthermore, since distribution networks are strong—built so as to accommodate electric space heating in homes and offices—both connections and other infrastructure have had sufficient capacity to accommodate the demand from electric vehicle charging. Finally, since

1. Some respondents use timers to activate their chargers, presumably explaining the peak in Hour 4.

network owners are allowed to charge for upgrades associated with new or stronger connections, they have been able to finance new investment where it has been warranted.

So far, due to the ability of the network to accommodate the charging of electric vehicles—as well as the relatively modest short-term (hour to hour) variations in prices in the hydro-dominated Norwegian electricity market—there is little use of "smart" technologies aimed at shifting demand to avoid capacity constraints or high-price periods.

Skotland, Eggum and Spilde (2016) estimate that the government target of half the fleet of vehicles be electric by 2030 will increase electricity consumption by 4 TWh per year, i.e. by about 3 per cent of total annual consumption. The maximum energy consumption per hour would be 700 MWh and would occur at night. Compared to an average maximum consumption of 4 kWh/h for households on a cold day (with a peak at 19.00), the charging of electric vehicles would increase the maximum by approximately 0.5 kW on average, i.e. by approximately 12.5 per cent. Based on assumptions on the location of electric vehicles and their charging patterns, as well as detailed information on distribution networks, Skotland, Eggum and Spilde found that, in most areas, the distribution network is sufficiently robust to handle the increase in demand from electric vehicles. However, in areas with low network capacity, a high share of electric vehicles and a high correlation in charging behaviour among owners, both transformers and lines may be overloaded. In areas with weak distribution networks, quality of supply (i.e. voltage level stability) may also be challenged.[2] Since much of the distribution network will be replaced in the years up to 2030 due to age, it is argued that the necessary up-grading may be taken care of as part of this process.

Figenbaum (2018) questions the realism of the Norwegian transport electrification policy. He argues that the penetration of electric vehicles is the result of strong government-created incentives and of a stable long-term policy, but that this is not enough to meet the target of only selling zero-emissions vehicles by 2025. Until now, the main electric-vehicle user group has been multi-vehicle households that have replaced one conventional vehicle with an electric vehicle. After 2025, all single-vehicle households must buy electric vehicles, and electric vehicles must replace all vehicles in multi-vehicle households. New electric vehicles with longer range may help, but traffic on peak travel days could become a major barrier. As it may not be economically sensible to build charging infrastructure capacity to absorb these peaks, users will be confronted with a trade-off between daily cost and time savings on the one hand, and longer stops and charging queues on long distances, on the other.

Wangsness, Proost and Rødseth (2018) argue that current policies may lead to a massive penetration of electric vehicles but also to much more congestion and a decrease in the use of public transport.[3] Better policies require efficient pricing of road congestion, a greater use of public transport and incentives for consumers to choose the most efficient combination of vehicles. Such policies may result in a less extreme penetration of electric vehicles, but will achieve a better transport equilibrium and substantial resource cost savings, leading to higher welfare.

2. Electrical equipment such as electric vehicle chargers represents more of a challenge for supply quality in Norway than in other European countries (Skotland, Eggum and Spilde, 2016) due to the fact that about 70% of the distribution network in Norway is of the 230 V IT type, as opposed to the 400 V TN type that is common in other countries, and which most electrical equipment, including chargers, is built for.

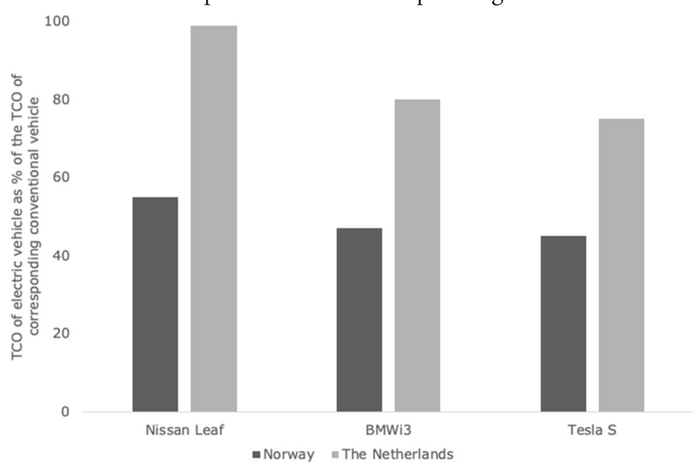
3. Fridstrøm and Østli (2017) undertake a cost-benefit analysis of the Norwegian electric-vehicles policy, concluding that the cost per tonne $CO_2$ is moderate to high.

## 3. THE NETHERLANDS

In order to encourage electric driving, the Dutch government has introduced various tax incentives (see Table 1), such as total exemption from registration fees and road taxes for electric vehicles, which are to be retained for zero-emissions vehicles until 2024 (NEA, 2019A). The initial increase in the number of plug-in hybrid electric vehicles between 2012 and 2014 was linked to tax incentives targeted at company cars (CBS, 2018), but after these incentives were phased out the number of plug-in hybrid electric vehicles has remained approximately constant, cf. Figure 1.[4] Even if these incentives have lowered the cost of electric vehicles relative to conventional counterparts, their power is substantially weaker than in Norway, cf. Figure 3. Specifically, in Norway the total cost of ownership of electric vehicles is approximately half of the corresponding conventional vehicles, whereas in The Netherlands the cost ranges from three-quarters to almost the same as for the corresponding conventional vehicle.

**FIGURE 3**

Cost of electric vehicle ownership[a] relative to a corresponding conventional vehicle,[b] per cent.




[a] Cost of ownership equals purchase cost (incl. taxes and subsidies) plus the present value of operating costs (incl. fuels and annual taxes, but not insurance, repair and maintenance costs) and less resale value.
[b] The corresponding ICE vehicles are as follows: Nissan Leaf: Honda Civic 1.6 i-DTEC; BMW i3: BMW Series 1, 116d; Tesla Model S: Audi A7 3.0 TDI ultra.
Source: Lévay et al. (2017).

The Dutch government has co-founded the installation of public and semi-public charging points, including fast-charging points, largely through so-called Green Deals, initiatives that facilitate cooperation between private firms, civil society organisations and local and regional governments, with the aim to remove barriers encountered during implementation of various innovations.

In addition to general financial incentives offered by the central government, local governments have also been encouraging the adoption of low-emissions vehicles through a number of measures. Municipalities of big cities offer subsidies for the purchase of electric vehicles, in-

4. The Environmental Investment Rebate (MIA) offers an additional deduction of up to 36 per cent of the investment costs for an environmentally friendly investment, including both electric vehicles and charging points (MEA, 2017; NEA, 2018). In addition, the so-called Vamil—an economic incentive targeting small and medium enterprises—has the objective of stimulating the dissemination and market penetration of new environmentally friendly technologies (EC, n.d.).

cluding private cars, taxis and lorries. Additionally, some municipalities offer subsidies for the installation of charging stations and the scrapping of polluting passenger and delivery cars. A number of tenders have been issued for installations, often experimenting with smart charging technology (NEA, 2018).

We are not aware of systematic studies of early adopters of electric vehicles in The Netherlands, but data presented by CleanTechnica (2020) suggest that they share many of the same features as their Norwegian counterparts, including the reasons why they chose an electric vehicle. Most have access to home charging, although a somewhat higher share (15 as opposed to 5 %) has public charging stations as their primary charging station in the Netherlands than in Norway; charging patterns are however quite similar.

More than a third of all homes in the Netherlands are flats, out of which only a small part has a private parking space, around a third have access to parking space on a common ground, while the rest have to park on the street (ECORYS and EVCONSULT, 2017). Various cities across the Netherlands have created programs enabling electric-vehicle owners without access to home or work charging to apply for curb side charging stations.

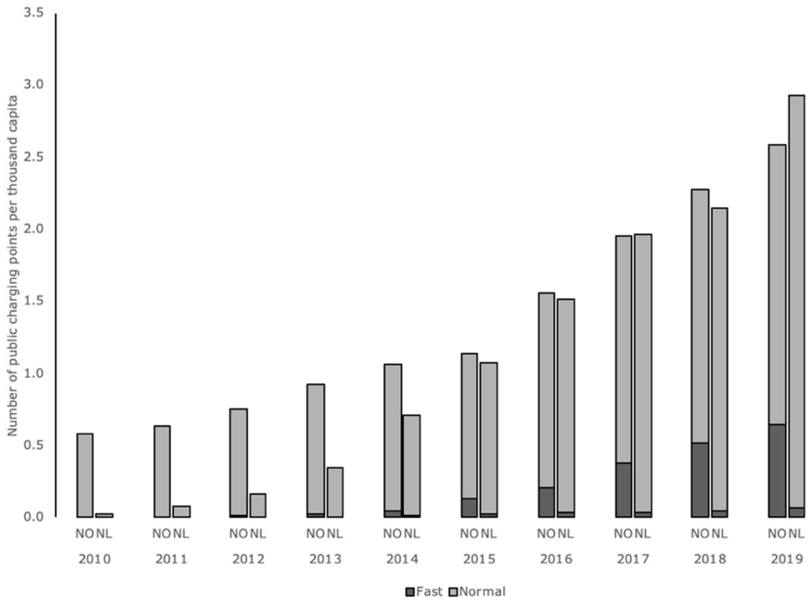
As pointed out immediately above, the charging needs in the Netherlands are primarily met by private charging at home or at work. Public charging infrastructure includes both stations accessible 24 hours a day (seen as "the last resort" alternative, i.e. to be used when other options are not available, according to the Ministry of Economic Affairs, MEA, 2017) and 'semi-public' charging points, installed at shopping malls and on the parking places of private facilities which are accessible to all although access might be restricted due to, for instance, opening hours. Figure 4 shows the development of public charging stations, about half of which are 'semi-public' (NEA, 2019b); the number of private charging points is estimated to be about three times the number of public charging points. Interestingly, the trajectories for The Netherlands and Norway are quite similar in per capita terms, although the share of fast-charging points is considerably higher in Norway.

The role of the government in the rollout of charging infrastructure has evolved over the last years. Public charging stations were initially constructed by a consortium of network companies in big cities and along main roads, with the hope that an initial uptake of electric vehicles in cities would encourage further investment in charging infrastructure in surrounding municipalities. Now, the aim is to create a functioning market model where a mix of private, semi-public, public and fast-charging points is available (MEA, 2017).

The largest manager of public charging stations EVnetNL, an initiative set up by several electricity network companies, built around 3,000 public charging points between 2009 and 2014 (Helmus et al., 2018). Local and regional governments had the possibility to apply for a charging point and EVnetNL managed the procedure. These charging points were usually placed in the vicinity of public facilities where occasional use was expected, such as shopping centres and sporting halls. EVnetNL also offered demand-driven rollout: the owner of an electric vehicle could request a charging point near home. Since 2016, some municipalities have taken over charging stations and outsourced their management to private companies (NEA, 2018).

The City of Amsterdam prioritises electric vehicles in applications for city parking. Additionally, in cooperation with Vattenfall, the local network owner Liander, the infrastructure competence centre Elaad and the University of Applied Sciences Amsterdam, the city offers two types of charging points: regular and Flexpower. Flexpower stations supply normal power

**FIGURE 4**
Number of public charging points per thousand capita.




Source: EAFO (2020), Eurostat, authors' calculations.

between 06.30 and 18.00, more power between 21.00 and 06.30 (as well as in sunny weather during day time) and less power between 18.00 and 21.00 (City of Amsterdam, n.d.).

In parallel with regular-speed charging points (below 22 kW), the network of fast-charging infrastructure is also developing rapidly; this is connected to the medium-voltage network and offers maximum power connection of up to 350 kW (van Amstel, 2018). Some cities are investing in such infrastructure; for example, the city of Amsterdam has installed a number of fast-charging points as a result of agreements between the municipality and the taxi sector (NEA, 2019A). Many initiatives are however private; for example, all McDonalds parking lots will eventually be equipped with a fast-charging station, Nuon is installing a network of fast chargers, Lidl has installed fast chargers (with no charging fee) at its stores in a partnership with ABB, Fastned is installing some along the roads, and Shell, in cooperation with Allego, has installed and manages fast chargers at its service stations (NEA, 2017; 2018; 2019).

Belgium, Luxembourg and The Netherlands have signed an agreement that promotes "cross-border access to e-Mobility services in the Benelux countries", enabling electric-vehicle drivers to charge in all three countries using the same access card/app and ensuring transparency of prices (NEA, 2018).

The attitudes of potential users towards proposed technical solutions for smart charging are investigated by Hoekstra and Rafa (2017). People agree to make smart charging the default choice at home under the condition that they can control charging and are able to override the smart charging option. They were especially interested in larger—i.e. doubling or tripling—increases of charging speed.

A recent survey by the The Netherlands Knowledge Platform for Charging Infrastructure (NKL) on electric vehicles owners' needs highlights the importance of transparency of prices (NKL, 2019a). The price schedules tend to be opaque, and prices typically depend not only on the charging point operator but also on the mobility service provider (idolaad, 2016). Sometimes payment is based on a volumetric fee, sometimes also taking charging or connection time into account.

The average Dutch car drives 37 km per day, meaning that for most of the day, it stays still. If a 37 km trip requires around 8 kWh—which is about 2.5 hours charging with the lowest speed (single phase 16A and 3.7 kW)—the potential for using smart charging and adjusting the starting time of charging and power level to the conditions on the grid seems a plausible option (EDSO, 2018). Many projects and initiatives investigate the potential of smart charging. For instance, the province of North Brabant and Enexis have cooperated on a smart-charging project including the installation of 255 stations offering smart charging outside of peak hours (NEA, 2017).

Another solution is that of so-called charging plazas: a number of charging stations sharing a single connection (NKL, 2019). In 2018, one of the largest charging plazas in the Netherlands was opened in Eindhoven (Allego, 2018). The plaza counts 50 Allego charging stations, offering a combination of smart, regular, fast and ultrafast charging (NEA, 2019A). The business case of charging plazas has more potential than that of charging stations: the capacity charge must be paid for a single grid connection only and a plaza can accommodate several vehicles at the same time, which is expected to increase the number of transactions. However, at present, grid operator costs remain higher for a charging plaza than for a charging station (NKL, 2019b).

The average cost of a new charging station has been decreasing fast and a further drop is expected, although at a slower rate (NKL, 2018a). While investment (one-off initial) costs came down by approximately 30 per cent and annual operating (periodic) costs by 40 per cent between 2013 and 2018, only 15 and 5 per cent reductions, respectively, are expected over the next decade. This indicates that costs have been optimised; further gains might involve innovative charging infrastructure solutions, e.g. charging hubs/plazas.

Another important element of the market model in the Netherlands is standardisation and interoperability of the charging infrastructure. ElaadNL has been involved in the development of standards, which enable efficient communication between the various parties involved to ensure interoperability in operation and payment (Hall and Lutsey, 2017).

In order to facilitate the uptake of charging infrastructure, The Netherlands Knowledge Platform for Charging Infrastructure maintains an overview of standards, describing application and construction, environment and location, management and monitoring, functionality, design, engineering and safety, back offices and interfaces, smart charging and security (NKL, 2018b). The standards are classified according to whether they are required (based on official standards, directives, laws or regulations) or desired. Among the payment standards, it is stated that a charging station must be accessible through valid charge passes (authentication apps) from various providers. The contractor is expected to sign contracts with mobility service providers (including foreign providers). One of the desired functionalities of a charging station is its ability to accommodate charging for one-time users through a payment option without subscription, for example using a smartphone. Payment covering both parking and charging (when applicable) is also encouraged. Among actions recommended to be included in a tender for charging infrastructure (but with potential incidental deviations) is to allow users the choice of power supplier.

## 4. DISCUSSION

While developments on the supply side of the electric vehicles market have been a driver for the increase in the number of these vehicles in recent years, public policy has been crucial. In terms of user experience, improved models can now compete with conventional vehicles. Still, not all countries have experienced a rapid rise in electric vehicle numbers. In fact, Norway's leadership in that sphere is no doubt largely due to the generous subsidies and benefits enjoyed by buyers and owners of electric vehicles there. Notably, based on Figures 1, 3 and 4, it is evident that while the development of charging infrastructure has been similar in Norway and The Netherlands, the financial incentives and growth of the number of electric vehicles have been much stronger in Norway. Moreover, both the rise and the subsequent drop observed in purchases of plug-in hybrids in the Netherlands came as a consequence of, first, the introduction and, later, the withdrawal of tax incentives for companies to lease such cars. Thus, so far it has been costly for governments to raise the market share of electric vehicles; this, however, will change as their prices (largely driven by cost of batteries) fall.

Apart from tax incentives, which typically benefit all electric-vehicle owners in a given country, many cities have taken a lead in encouraging the penetration of electric vehicles through preferential policies in areas such as traffic, parking and charging. Clearly, this benefits people living in and near cities. It is therefore not surprising that electric vehicle ownership is especially concentrated in these areas. This may also be explained to some extent by the fact that, so far, most electric vehicles have had limited driving ranges and hence are mostly suited for local transport.

The fact that electric vehicles are mostly used for short distances, may explain why most people prefer charging at home or at work rather than using public charging stations. Moreover, the number of electric vehicles has grown considerably even with limited access to public charging. In other words, there is a substantial group who are willing to buy an electric vehicle, even with little access to public charging infrastructure. For others, especially households without access to private charging, public infrastructure is crucial. Public infrastructure, in particular fast chargers, will also be warranted to accommodate long-distance traveling in electric vehicles.

We find a clear pattern in charging behaviour, with peaks in the morning (charging at work) and in the afternoon and evening (charging at home). In the Netherlands, only one car in fifty is electric. Hence, increased peak load does not yet seem to be a problem for the electricity infrastructure. Neither is it in Norway, which has five times the stock share of the Netherlands. This is largely due to the strong electricity infrastructure in Norway, which is built for electric space heating. However, if the policy aim of a fully electrified car fleet was to be realised, and in the absence of countervailing measures, problems are likely to occur in many countries, especially where the infrastructure is not as strong as in Norway.

Table 2 below gives some indication, for a selection of countries, of the potential impact on the power system of full penetration of battery electric vehicles.[5] The impact on aggregate demand would lie in the range of 20-25 per cent for most of the countries, although it would be substantially lower for Norway (6%) and somewhat higher for The United Kingdom (27%). Since most charging at present takes place in residential areas, the relative impact on household consumption may be a better indicator of the challenges faced by distribution networks. This

5. The impact of a lower than full share can of course be calculated pro rata.

indicator lies in the range of 80-100 per cent for most countries. The impact is smallest in Norway (18%) and France (52%), while Italy has the largest impact (111%).

**TABLE 2**
Potential impact of electrification of the vehicle fleet*

| | **Electricity consumption, MWh/cap p.a.** | | **Passenger cars** | | **EV electricity consumption with 100% stock** | | |
|---|---|---|---|---|---|---|---|
| | Total | Households | #/cap | Distance, km/car p.a.** | MWh/cap*** | Share of total consumption, % | Share of household consumption, % |
| **Norway** | 23.1 | 7.5 | 0.52 | 12,851 | 1.3 | 6 | 18 |
| **France** | 6.8 | 2.4 | 0.48 | 12,997 | 1.2 | 18 | 52 |
| **Netherlands** | 6.5 | 1.3 | 0.49 | 13,022 | 1.3 | 20 | 97 |
| **Germany** | 6.4 | 1.6 | 0.56 | 14,107 | 1.6 | 25 | 102 |
| **Spain** | 5.2 | 1.5 | 0.51 | 12,535 | 1.3 | 24 | 84 |
| **Italy** | 5.0 | 1.1 | 0.63 | 9,596 | 1.2 | 24 | 111 |
| **United Kingdom** | 4.7 | 1.6 | 0.47 | 13,177 | 1.2 | 27 | 78 |

* Calculated from data sourced from Eurostat.
** Source Odyssee-Mure (2020), except Norway which is calculated from Eurostat data.
*** Based on 0.2 kWh/km

When considering the indicators above, we should keep in mind that full electrification of the vehicle fleet would take place over decades. In other words, there is time for countries to respond. However, if consumer charging behaviour does not change, peak demand in these—and other—projections could rise considerably more than energy demand. As explained in the section on Norway, the impact on peak household demand with a 50 per cent stock share is projected to be approximately 12.5 per cent; the impact on average household demand would be 9 per cent according to Table 2 (calculated pro rata). In most other countries, the proportional impact on peak demand would be considerably larger. This could put a strain on electricity infrastructure, from generation to networks. Depending on how charging infrastructure develops, local effects could be even stronger, leading to an overloading of distribution infrastructure in certain locations at specific times.

Such negative outcomes are, however, not a foregone conclusion. Since it is the peak demand during specific times of the day and at certain points, rather than the energy demand as such that could be problematic, it is critical to change the behaviour leading to those problems. In Norway and The Netherlands —as in most other countries—there is only limited time-of-use (and geographical) differentiation of electricity prices—and none for tariffs—and hence there is little price incentive for shifting charging. More will thus be warranted to solve the localised problems in distribution networks. For this, a much more granular approach would be needed, reflecting not only overall supply and demand in the market at a given time and, perhaps, at a given node, but also the situation in a given neighbourhood or even a given street. Moreover, time-of-use pricing would have less of an impact on demand for charging at public charging points than at homes or at work. A change in regulation, e.g. on when and where charging can take place, rather than a change in the tariff and pricing structure, could be more appropriate in such cases. As evidenced by the experience in Amsterdam, it is possible to utilise relatively simple measures to affect charging behaviour. The "Flexpower" network of "intelligent" public charging stations was launched recently, with the aim of reducing load from electric vehicle charging during evening peak hours, and instead shifting it to hours when load, net of solar generation, is low.[6]

Electric vehicles not only pose challenges for the power system, but also create opportunities. A large fleet of plugged-in electric vehicles forms a huge storage facility in the aggregate.[7] The average non-commercial vehicle is parked more than 90 per cent of the time. Thus, if infrastructure is there to connect most stationary cars to the grid, and if smart charging technology is in place, there is a technical potential to harness this storage. If this technology is successfully brought to the market, electricity sourced from electric vehicles could provide flexibility and balancing services when needed. This would be of crucial importance for the power system, especially in a system with a high share of variable renewable energy (wind and solar). But as the two country cases show, technology alone is not sufficient; a change in charging behaviour is also needed if this potential is to be harnessed. For this to happen, vehicles need to be plugged into the grid while they are parked, the vehicle-to-grid technology has to be developed and in place, and market agents—aggregators—need to be operating and to have entered into contracts with electric vehicle owners for the use of their (mobile) batteries. One challenge in this regard is simply having enough charging (or de-charging) points for parked vehicles. Electric vehicles also need to be allowed to stay connected without penalties—i.e. even while not charging. Given the scarcity of public charging points at present, it is not surprising that such penalties exist, as is the case in Oslo.

Both the Netherlands and Norway have adopted mostly decentralised approaches to charging infrastructure.[8] However, in both countries, such infrastructure has developed in line with the fleet of electric vehicles and charging facilities do not seem to provide an obstacle to further growth of the fleet. The Norwegian experience is perhaps of particular interest, given the unusually high penetration of electric vehicles there. The fact that distribution networks are guaranteed financing of necessary upgrades from users has clearly played a part in facilitating the connection of charging points. This system also provides appropriate incentives for placement of charging points, as owners of all charging points—both at charging stations and at home—must pay the full network connection cost imposed on the system. However, from a transport policy perspective, one of the drawbacks of this policy is that it may raise the costs of charging—especially home charging where location is not really a choice of the user—and, hence, may slow down the adoption of electric cars. This has not been the case in Norway so far, due to the limited need for infrastructure upgrades in residential areas and to the efficient location choice for charging stations. Where upgrades have been required, the associated costs are limited (typically multi-home dwellings).

The Netherlands has developed more of a bottom-up approach to account for the fact that a large proportion of people live in multi-home dwellings without access to a garage or a private parking space. Citizens can request that a charging point be set up near their home. Their request is then evaluated from a demand, cost and grid perspective. This seems a sensible approach, likely to lead to reasonable cost efficiency, and allowing for the reduction of congestion and capacity problems in the network, although this will depend on the implementation.

6. In Italy a "time-of-use" power limitation, higher by night than the contractual limit applicable in the remaining hours, is being considered. See ARERA (2019) part IV.

7. In a longer-term perspective, used batteries may also become an important stationary storage facility (Element Energy, 2019).

8. As explained in Baldursson et al. (2019), Luxembourg has taken a somewhat different approach to creating a charging infrastructure for electric vehicles. There, responsibility for ensuring the necessary infrastructure has been vested with electricity network companies, who have produced a comprehensive national scheme, based on public tenders, to ensure timely roll out.

## 5. CONCLUSION

In this paper we have studied the development of electric vehicles and the associated infrastructure in The Netherlands and Norway; these countries are leaders in this area which makes them interesting cases for study. Development in these countries indicates that the uptake of electric vehicles has so far essentially been driven by financial and other benefits offered to potential buyers. These benefits are stronger in Norway and the market share of electric vehicles in correspondingly higher.

Most owners of electrical vehicles prefer charging at home or at work. Hence, a partial electrification of the vehicle fleet may be achieved even with limited public charging infrastructure, but the market will then be limited to buyers with access to private charging who travel mostly locally. For increased penetration of electric vehicles public infrastructure is needed. In both cases studied, infrastructure has tended to follow the development of electric vehicles and, so far, lack of charging facilities do not seem to have hindered further growth of the fleet.

In both cases studied the impact on the electricity industry in general and electricity networks in particular has so far been limited, even given the relatively high penetration of electric vehicles. In most countries this is likely to be different when the majority of the car fleet is electric. Smart charging solutions—incentive driven or command-and-control based—must then be adopted to change charging behaviour in order to ease local strains on networks and reduce peak electricity demand. Electrical vehicles themselves may become part of the solution as storage if vehicle-to-grid technologies are successfully deployed.

Policies for supporting the adoption of electric vehicles for individual use tend to be considered mostly from the environmental perspective. The case of Norway indicates that it is also necessary to consider them as a part of transport policy, including consideration of issues such as road congestion and incentives for using public transport.

## ACKNOWLEDGMENTS

This article is based on Baldursson, von der Fehr and Lazarczyk (2019), a study written for the Centre on Regulation in Europe (CERRE, www.cerre.eu). The study and this article reflect the views of the authors only; it may not reflect the view of CERRE or its members.

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