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Fast charging – Evidence from a full scale laboratory

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Executive Summary

Norway is the largest Battery Electric Vehicle (BEV) market per capita in the world. The share of the passenger vehicle fleet passed 7% at the end of 2018, and users have access to 1100 Combined Charging System (CCS)/Chademo standard fast chargers located in more than 500 different locations. This paper analyses the usage pattern of these fast chargers using a dataset from two large operators covering most of their charging events between Q1 2016 and Q1 2018. The target of the analysis was to understand the fundamental factors that drive the demand for fast charging, so that they can be taken into account when dimensioning charge facilities. The data displays clear variations in charge power, charge time and charged energy between winter and summer, and is also affected by public holidays, charger locations, and technical characteristics of the vehicles. The charge power is clearly reduced in the winter compared to the summer, while the charge time is longer. The charged energy is higher on typical vacation days for chargers in main travel corridors. Some charge events have a particularly low charge power which may be due to users fast charging a cold battery at a high State of Charge (SOC) in a vehicle with passive battery thermal controls.

Keywords: fast charge, infrastructure, user behaviour, market development, policy

1 Introduction

BEV users tend to charge their BEVs at four locations [1,2], (1) at or near home, usually overnight, (2) at workplace or commuting locations, supporting longer distance commutes (3) at public locations, i.e. stores, shopping centers, transport terminals, parking, and (4) during stops in travel corridors, while travelling from origin to destination. Low cost home charging is seen as a major advantage of Battery Electric Vehicles (BEVs). The long charge time is on the other hand seen as a major drawback that have limited the use of BEVs for long distance trips [1,2].

The use of BEVs can become easier and more flexible with the ability to fast charge [1,2]. Fast chargers positively influence the user perception of the relative advantage of BEVs compared to Internal Combustion Engine Vehicles (ICEVs), and support the diffusion of BEVs according to Rogers' theory on the diffusion of innovations [3]. Fast chargers installed in areas where BEV owners live and work complement home-charging, allowing users to expand their driving range and acting as a safety net when users run out of electricity. BEV owners can fill energy from fast chargers during long distance driving, which is however more time consuming than filling with fossil fuel, and more costly than home charging [2,5].

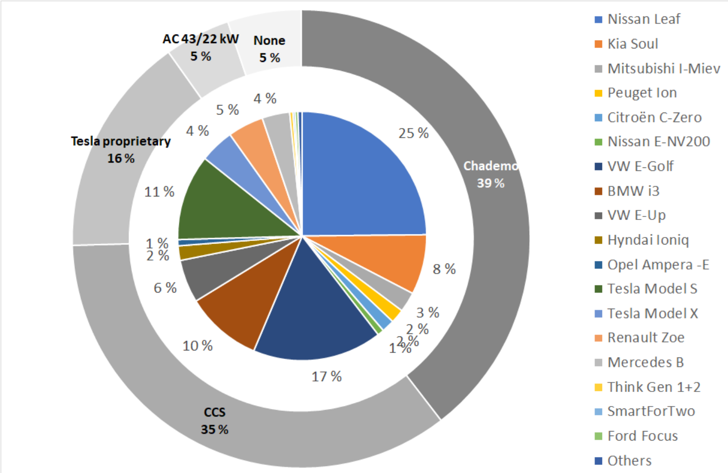
Few have analyzed in depth the actual usage of fast chargers at a national level, and the parameters that influence the user experience. The purpose of this paper is therefore to do an in-depth analysis of the use of fast chargers in Norway, to identify the fundamental factors that influence the utility of fast chargers (and their corresponding variability over years, weeks and days).

This paper starts off with an introduction to the BEV fleet and fast charge infrastructure in Norway in section 2. Section 3 presents the datasets and methods used in the analysis. The results are presented in Section 4 followed by a Discussion of the results in Section 5.The conclusion with recommendations is in Section 6.

2 BEVs and fast charging in Norway

Norway is the largest per capita BEV market in the world, with a BEV share of new vehicle sales of 31.2% (in 2018) [7]. When including second hand vehicle imports, the total number of first time BEV registrations was 58024 [7]. BEVs reached a total passenger vehicle fleet share of 7.1% at the end of 2018, whilst Plug in Hybrid vehicles (PHEVs) reached 3.5%. The total share of Plug in Electric Vehicles (PEVs) has thus passed 10% [8].

39% of the Norwegian BEV fleet use the Chademo DC fast charge standard, 35% use a combined charging system (CCS) and 16% use the Tesla standard [5], as seen in figure 1. Another 5% of the fleet can be semi-fast or fast charged at 22 or 43 kW AC [5]. 5% of the fleet cannot be fast charged. The datasets used in this paper do not cover the Tesla Supercharger network. The average non-Tesla BEV battery in the fleet has a nominal battery size of 26 kWh [5], with the distribution of battery sizes shown in figure 1. The average vehicle can thus fast charge about 15.5 kWh of energy, assuming a fast charge State of Charge (SOC) window of 60% of the batteries nominal capacity[1] [5]. The majority (88%) of these vehicles can theoretically charge at 50 kW [5], but Fastned found that the fast charge power for some vehicles will be much less than 50 kW even under optimum conditions [8]. About 64% of the vehicles use passive battery thermal management [5], which will not be able to keep an optimal battery temperature, leading to a large reduction in practical charge power in cold [5,10,11,12,13,14,15] and hot climates [16]. In general Norway has cool summers, and temperatures above 30°C are rare. Winters can be quite cold, typically in the range of 0 to -10°C in cities, but occasionally down towards -20°C. In rural inland, -30°C and even colder is also possible but fairly rare in most places [5].



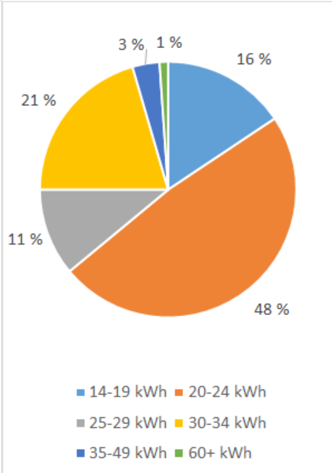


Figure 1. Model fleet shares and share of charging systems (left) [5] and non Tesla BEVs battery size split (right)

About 1000 Chademo/CCS 50 kW[2] fast chargers were installed in Norway at the beginning of 2018, in about 500 locations [5]. Each charger is capable of charging one vehicle at a time, either Chademo or CCS [5]. The locations can, as shown in figure 2, be classified according to their facilities, location and suitability in supporting driving in 'corridors' [5]. Most chargers support corridor travel, as main roads

[1] Lowest 20% SOC is less useful especially in the winter, and above 80% SOC the charge power ramps down fast.

[2] Less than 2% of these chargers could deliver more than 50 kW.

follow valleys where people live and economic activity takes place. The most typical locations are at (or next to) fuel stations and food stores, followed by shopping centres and cafés [5]. The classifications are not mutually exclusive.

The build out of fast chargers has been supported by the government agencies Transnova and Enova, along with some provinces and municipalities [2,17,18,19], and led to the installation of at least two fast chargers every 50 km in all major transport corridors (with a couple of exceptions), to support long distance driving [2]. Fast chargers in cities are a fully commercial market [2], and in Norway cost typically 2.5-3.0 NOK/minute [2].

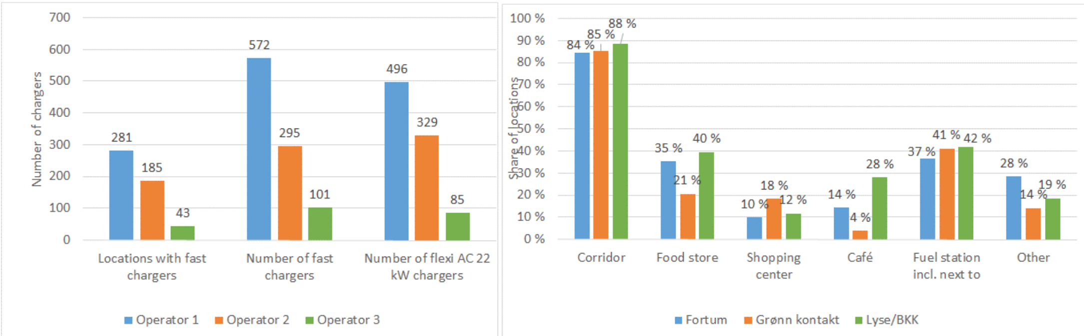


Figure 2: Number of fast chargers and location characteristics, Q1 2018, three main operators [5]

3 Method and materials used

Two datasets of fast charger use in Norway have been used in the analysis.

- Dataset 1 contains CCS/Chademo fast charge transactions in the charging network of operator 1, between Q1 2016 to Q1 2018. Each transaction contained an ID allowing the charging activity of individual users to be tracked over time (together with the minutes charged and the kWh energy charged). Each charger also had a unique ID. Sessions with very short durations (1 minute) or unrealistic charge power (>60 kW[3]) where removed from the dataset.
- Dataset 2 contains the majority of usage data, minutes occupied per charger and per plug, and for a subset the kWh delivered, for fast chargers in the network of operator 2 between January 2016 and January 2018. Unrealistic and faulty data were removed. User ID was not available in this dataset.
- The fast charge transaction and usage data from operator 1 and 2 are fully anonymous, thus the type of vehicle using the charger, or where the vehicle owner lives, is not known.
- The main strength is that these datasets contain the majority of charge sessions in two large networks.
- Due to confidentiality, the total charging volume and the charger locations will not be presented.

A survey, to complement the fast charger usage data, was also carried out:

- The survey was carried out in June 2018 [20], and had questions about fast charger usage and long distance driving behaviour of 3,659 BEV owners, and the driving behaviour of 2048 ICEV owners.
- Representative BEV owners were recruited from the EV association[4]. The response rate was 18%. The spread of owners and the spread of BEV models is representative of the total BEV fleet [20].
- The ICEV sample was reqruited from the Norwegian Automobile Association NAF, and is representative of the geopgrahical spread of its members. The response rate was 9.4%.
- A user survey has some inherent weaknesses such as memory bias and potential for misunderstanding, as well as the fact that some user groups may be less likely to answer online surveys. Nevertheless, a main advantage is that one can get more information about the fast charging needs, and experiences of users.

[3] the limit was not set at 50 kW as only whole minutes were available, so that 60 kW could not be ruled out
[4] BEV buyers get one year free membership in the association courtesy of the dealer/vehicle importer.

4 Results

4.1 Fast chargers in use per BEV in the fleet, geography of fast charger networks

Figure 3 shows the actual available number of chargers and locations for operators 1 and 2 based on when they first appear in the dataset, i.e. when the first charges have been carried out. Both operators invested heavily during 2017-2018 to build out national charging networks. The figure shows that the number of BEVs in the fleet per location was reduced from over 1200 to less than 500, and the number of BEVs per charger from about 800 to 330, for the sum of the two operators in this period of time. The geography of the networks of two national operators and one regional operator is shown in figure 4.

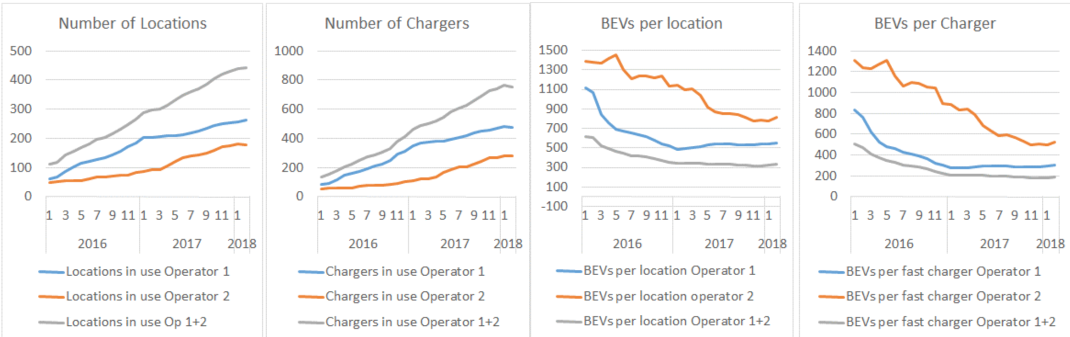


Figure 3. Number of locations and fast chargers in use per month for operator 1 and 2, and number of BEVs in the vehicle fleet per location and per fast charger. Dataset 1 and dataset 2.

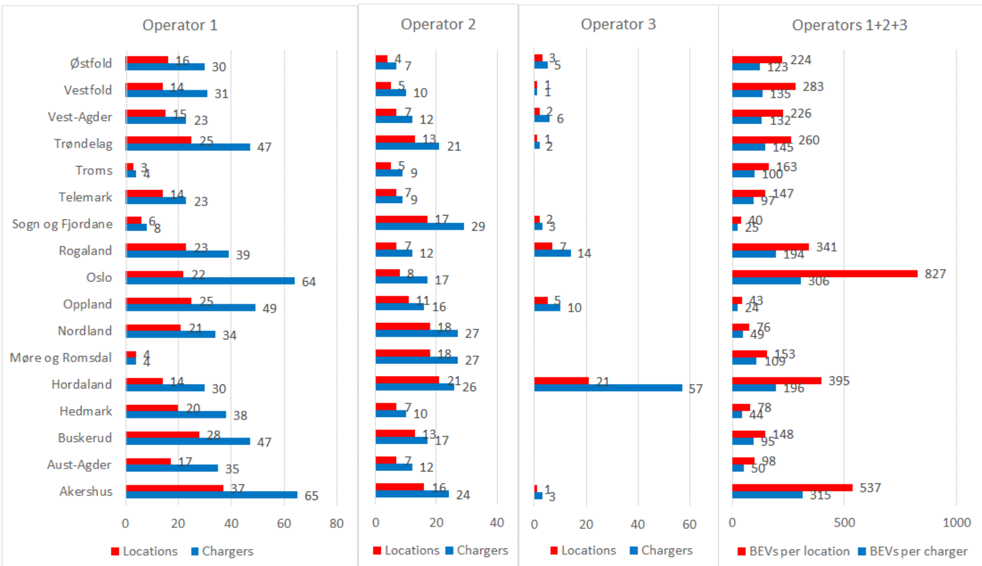


Figure 4. Geographical distribution of fast charger locations and total number of fast chargers. Vehicle fleet size status 01.01.2018, charge stations status per Q1 2018 (status Q3 for operator 3).

The number of BEVs per location and charger is much higher in Oslo and Akershus than elsewhere. Hordaland and Rogaland are other areas with high number of BEVs per charger and location, whilst Oppland, Sogn og Fjordane, Aust-Agder, Hedmark and Nordland are examples of counties with many fast chargers and few vehicles. This means that the number of vehicles per charger/location is low, in particular for the first two counties.

4.2 Fast charger usage

The use of fast chargers and the achieved fast charge power, time used and energy charged is heavily influenced by the fleet mix presented in section 2. As 64% of vehicles cannot maintain an optimum battery temperature due to passive battery thermal manament, the practical fast charge power drops signicantly in the winter season. This issue leads to a large variability between seasons and to some extent locations for the charge power and the charged minutes. These aspects are further investigated in this section.

4.2.1 Total use

The total national use of fast chargers could not be calculated from datasets 1 and 2 due to confidentiality. Therefore, the responses to the user survey, i.e. Dataset 3, was used to produce estimates of the total use. The user survey indicates that about 19 fast charges are performed on average per year by non Tesla users. A 2016 survey indicated 13-16 fast charges per year [1]. Using 13-19 fast charges per year as an uncertainty interval, the mid 2017 number of fast charge capable (non-Tesla) vehicles, the average annual km driven, and an average energy consumption[5], fast chargers can be calculated to have provided about 12-17 GWh of energy to BEVs in 2017, which was 4-6% of the overall estimated energy consumption of these vehicles.

4.2.2 Regional variation

Figure 5 shows the distribution between the provinces of the total number of fast chargers and total fast charge sessions (y-axis) for the two national operators and the largest regional operator[6], with the local BEV fleet share of the total national BEV fleet on the x-axis. If these parameters had been distributed evenly the dots would have collapsed to the green triangels on the mid line.

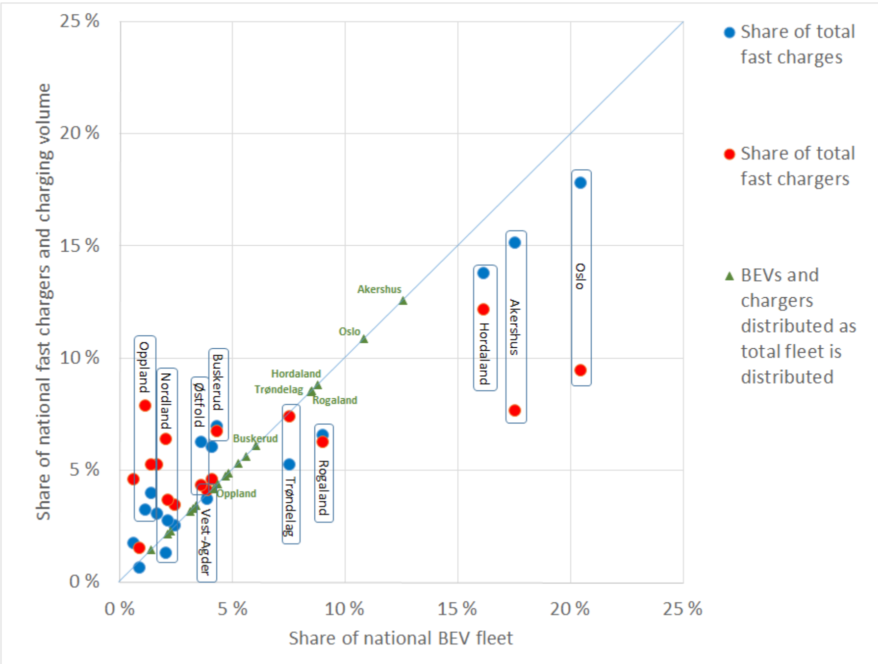


Figure 4. The provinces share of the total national charging volume (fast charge sessions) and installed fast chargers (y-axis) in 2017, and share of BEV fleet in mid 2017 (x-axis).

The provinces of Oslo, Akershus and Hordaland have the largest shares of the total BEV fleet, which is much larger than their shares of the overall vehicle fleet. The share of fast chargers is however much lower resulting in a high utilization of each charger (seen by the blue dots being above the red dots), especially for Oslo and Akershus. More chargers are needed in these provinces. Oslo is the largest city in Norway, with Akershus province surrounding Oslo. Hordaland has Norways second largest city, Bergen, and there also it seems that more fast chargers will be needed for their BEV fleet size. Nonetheless, the coverage is better than in the Oslo/Akershus area. The two provinces with Norway's 3rd and 4th largest cities, Trøndelag with Trondheim, Rogaland with Stavanger, have a better balance between demand and availability. Cities are now fully commercial fast charger markets, mainly without public support. In some cases, the provinces may still support fast chargers, for instance for commercial uses (e.g. taxis in Oslo).

[5] Average BEV 16000 km/yesr (dataset 3), average annual energy consumption 0.2 kWh/km, 95000 BEVs [21].
[6] Imputed as the lowest of the two other operators for each province.

On the other end of the scale, provinces such as Oppland and Nordland have a much higher share of chargers than their share of BEVs, and the use of each fast charger is low. A high share of these chargers have been built out with public support to establish national travel corridors between cities. They are underutilized Mondays-Thursdays, but used for long distance travels in the weekends. The latter cannot compensate for the limited local use on weekdays. The further away from cities the chargers are, the more variable is the demand between weekdays and weekends. Corridor chargers in rural areas far from cities are not yet commercially viable, but are however needed to build charging networks that support travel across Norway.

When longer range BEVs enter the fleets in the coming years it might be possible to locate fast chargers wider apart, and build larger stations in areas with better opportunities for local use (such as close to cities).

4.2.3 Seasonal variation

The total volume of minutes and kWh charged have increased rapidly over the years due growth in the number of chargers and vehicles. Nonetheless, seasonal effects in the demand for fast charging are clearly seen in figure 5.

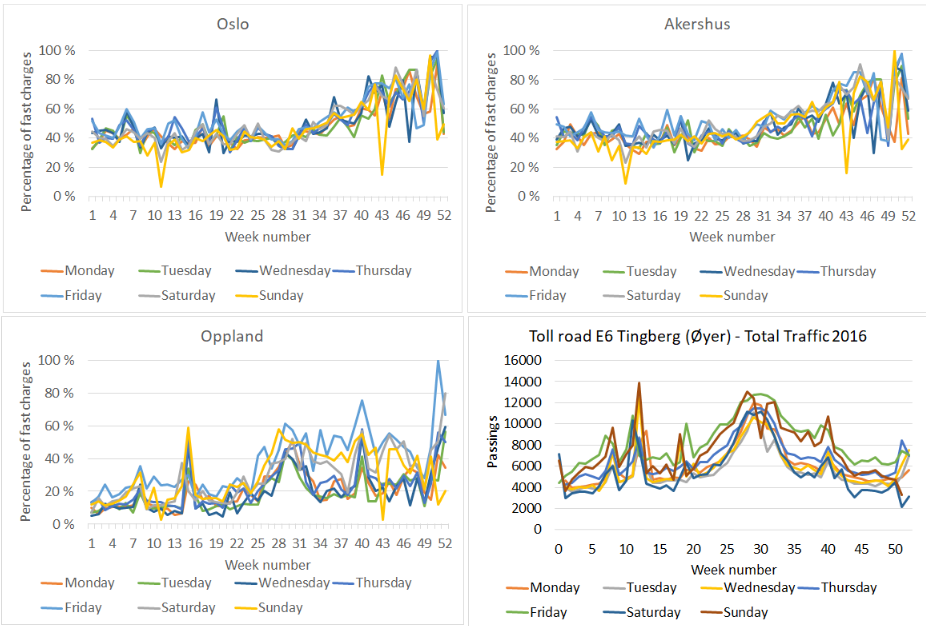


Figure 5. Development of charge volume over 2017 for three counties. Max value over year set to 100%. Dataset 1. Total LDV traffic flow (number of light vehicles) through a toll gate in the middle of Oppland province 2016 (Lower right, data not available for 2017). Source of toll road data: Toll road company [2].

The Easter period during week 15 (week 12 in 2016) caused large spikes in the use of fast chargers in Oppland, due to use by people going on vacation, while conversely the demand was low in Oslo and Akershus due to the absence of users (who were away on vacation). The same is true for week 40 which is a week with school vacation, as well as the summer vacation during weeks 28-32. The pattern in Oppland is consistent with the seasonal variability of toll road data from 2016 that shows the number of vehicles passing on the E6 main road in Oppland (Øyer Muncicipality). In Oslo and Akershus the variability of the demand is in general small over the year, but the total use increased.

4.2.4 Road type variation

The charge power should vary less over the year and be higher for fast chargers along high speed roads than for chargers mainly used by local users. The reason is that the batteries should be warmer in the winter in these locations and thus able to accept higher charge power. This seems to be the case, as seen in figure 6, when comparing motorway charging stations with other stations.

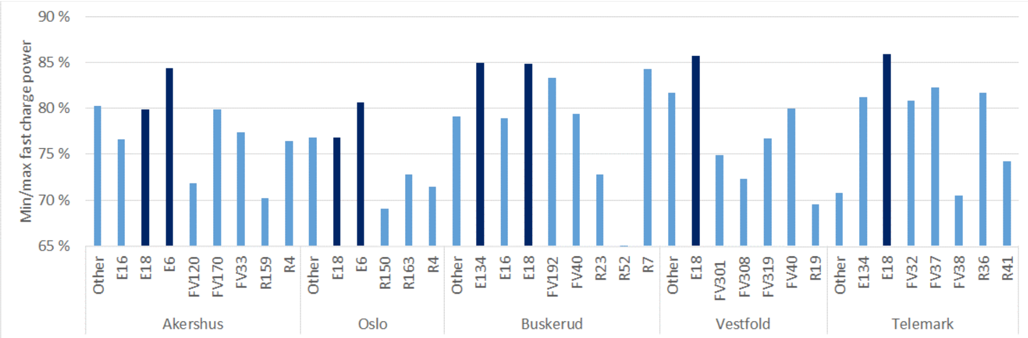


Figure 6. Variation between max and min average fast charge power per month for chargers along motorways (dark blue) and other road types (top), average energy charged (bottom), 5 provinces. E-roads are international main roads linking major cities and regions of Europe. R-roads are national main roads. F-roads are regional roads. Dataset 1.

One would also expect the average charged energy to be higher on high speed roads than on low speed roads, due to a higher energy consumption. In addition, users are more likely to be on a long distance trip on these roads. The latter assumption is not supported in the data, as seen in the same figure. It might be that the distance between fast chargers is shorter along the motorways so that users choose to charge less per charge stop, whereas the distance between chargers is longer on other main roads.

4.2.5 Intra-week and intra-day variation

The demand for fast charging is stable Monday-Thursday for all provinces, as seen in figure 7. On Fridays and Sundays, weekend traffic causes demand increases in provinces with high through traffic. In provinces with large cities (Oslo, Akershus, Hordaland, Trøndelag) the demand is much less influenced by weekend traffic.

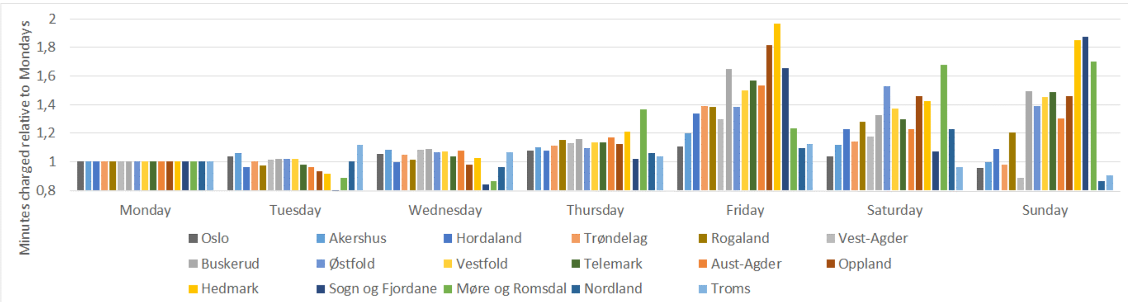


Figure 7. Minutes fast charged relative to Mondays by Province. 2017. Dataset 1.

The intraday demand follows a steady pattern where the peak demand is in the period 14-16 in the Summer and an hour later in the Winter, as seen in figure 8. Provinces with through traffic (example of Buskerud) have a large variation between weekdays and weekends.

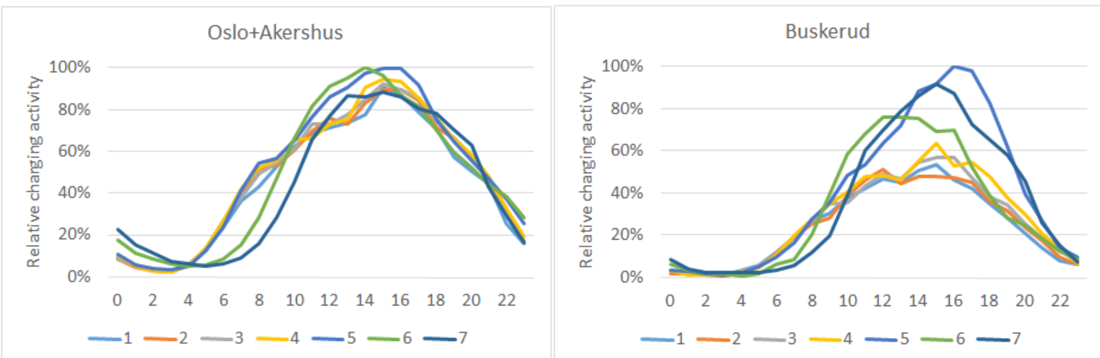


Figure 8. Average intraday (00-24) fast charge demand variation (minutes), Mondays-Sundays (day 1-7) per province. 2017. Datasets 1. The maximum data point has been set to 100%. The minutes of charge is attributed to the start hour.

4.2.6 Individual variation

The user ID in each transaction in the network of operator 1 could be used to track the users total charging activity over several years for a subset of the users within the charging network of this operator. It is, however, not possible to know when a user bought their BEV since they only appear in the dataset the first time they charge. It was therefore decided to analyse the charging behaviour in 2017 of users that had charged also in 2016. One cannot, however, know if some of the users sold their BEVs during 2017. It is assumed that those that had charged both in 2016 and 2017, remained BEV owners throughout 2017[7].

A large share of these users that charged in 2016 charged infrequently in 2017. A quarter used a fast charger only in one month, with another 16% in two of the months. The median was 3 months and the average was 4 months. Only 5% used fast chargers in more than 10 months. Figure 9 shows the median and average values and the distribution of the use of fast chargers, locations, and geographical spread, in terms of the number of provinces and municipalities chargers are used in. These users could however be using more than one operator's network so it thus represents the lower bound of their charging activity.

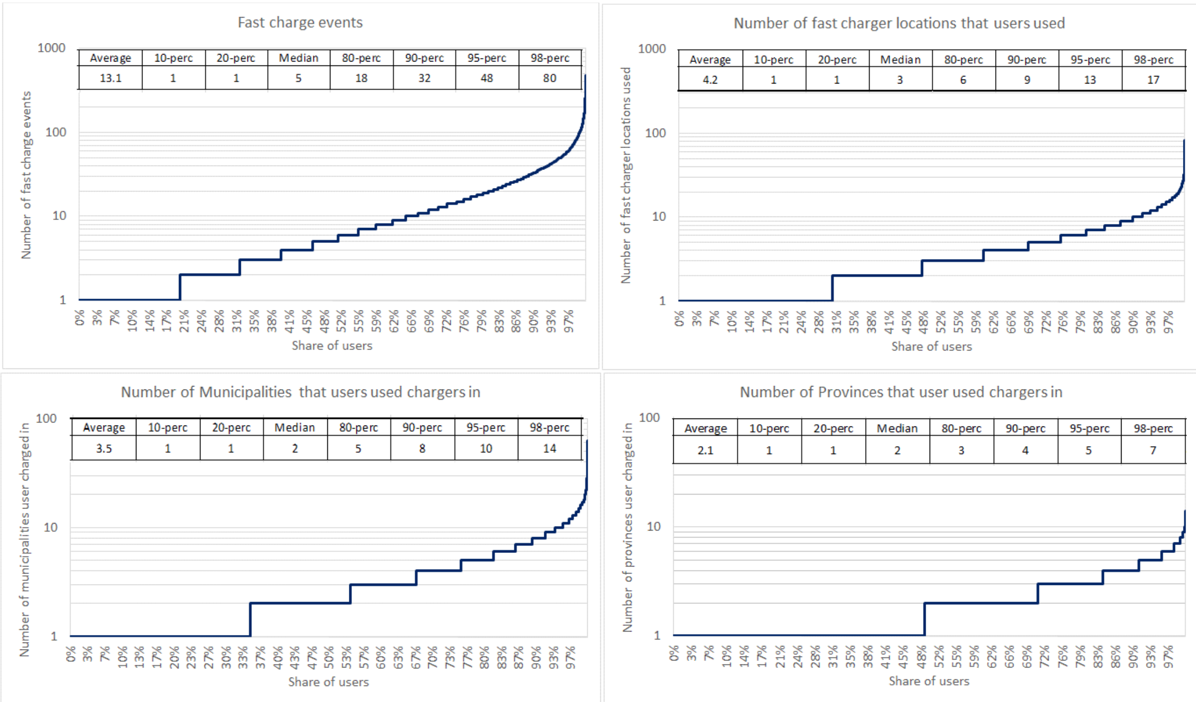


Figure 9. Number of fast charge events, fast chargers used in total, number of counties and municipalities fast chargers where used in during 2017 by users fast charging both in 2016 and 2017. Log scale. Dataset 1.

The upper 5%, i.e. the 95 percentile of users, charge on average every month, and 48 times per year from 13 locations in 5 provinces and 14 municipalities. The average value of 13.1 fast charges per year for all users is heavily influenced by the small share of these super users, as seen by the large difference between median and average values. These numbers, and data from user surveys about fast charging use, which indicate that few users only charge locally [1,4,20], suggests that there are four typical fast charge usage patterns:

1. Occasional user: likely use fast charger when they have a rare range problem
2. Local user: fast charge regularly to solve their everyday needs
3. Long distance trip user: fast charges to get to far-away destinations
4. Frequent user: people without home charging or professional users

[7] In the user survey, 93.8% said they will buy a BEV again. Only 0.4% would not, with the rest being unsure [20].

Occasional users charge 1-2 times per year and make up about 30% of the users. About 10% are frequent users. They charged on average more than 32 times per year in many different locations in different counties. The split between the remaining two categories is not possible to calculate. The user survey indicates however that it is uncommon to only fast charge in the users' own municipality, so many BEV users can be a combination of local users in everyday traffic and long distance users on vacation and weekend trips.

4.3 Variability in fast charge Power (kW), Time (minutes) and Energy (kWh)

4.3.1 National variability

The average fast charge session lasted 20.5 minutes and provided 9.6 kWh of energy at a power of 30.2 kW in 2017. A small share of the fast charge events have a surprisingly low power (<10 kW), as seen in figure 10. Energy and time follow a normal distribution skewed to the right whereas power is not normal distributed. The reason for the low charge power could be that some users charge from a 22 kW Type 2 AC plug that some fast chargers are equipped with. Another explanation can be that some people test out or use fast charge stations starting at a high SOC or that seasonal variations in the batteries fast charge capability is the problem.

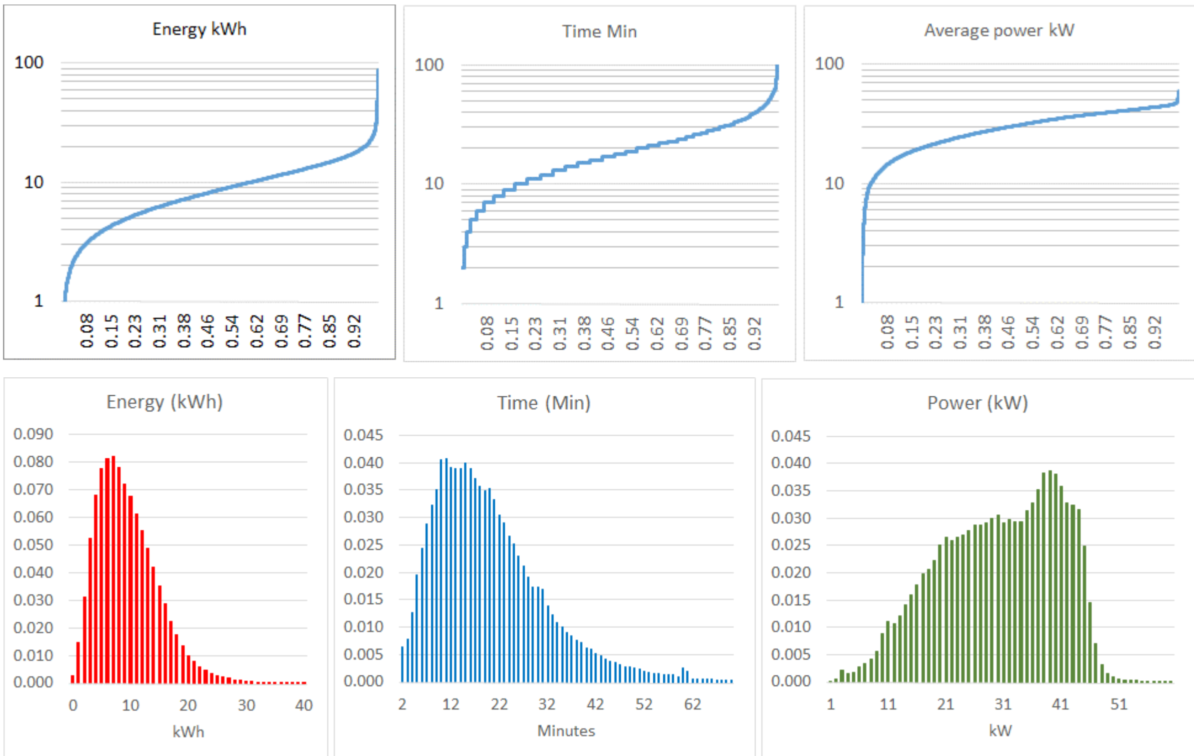


Figure 10: Spread of volume charged, time spent charging and average power for all charge sessions in 2017, share of valid number of charge events on x-axis, Log scale (top). Normal distribution of energy charged (bottom left) and time used charging (bottom middle) and distribution of average charge power (bottom right), share of valid number of charge events on y-axis. kW, Minutes and kWh have been rounded to nearest integer. Dataset 1.

4.3.2 Seasonal and geographical variability

The charge power, time (minutes), and energy (kWh) charged varies over the year, as seen in figure 11. The spread between users is large as shown in figure 10. The fleet is capable of accepting 15.5 kWh, i.e. 60% more than the average 9.6 kWh that is charged, indicating that the charge starts at a higher SOC or ends before 80% SOC. A theory is that users charge until 80% SOC regardless of season, although the range this amount of energy can cover is about 30% less in winter than in the summer.

The average charge power increases with increasing energy recharged and the difference between summer and winter is less when more energy is recharged, as seen in figure 12. The latter indicates a heating up effect of the battery when fast charging, so it gradually accepts a higher charge power.

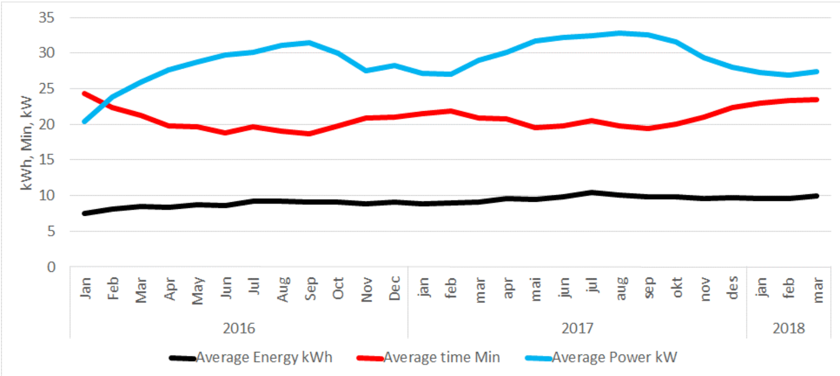


Figure 11: Variation over the year of average energy charged, time used and power.

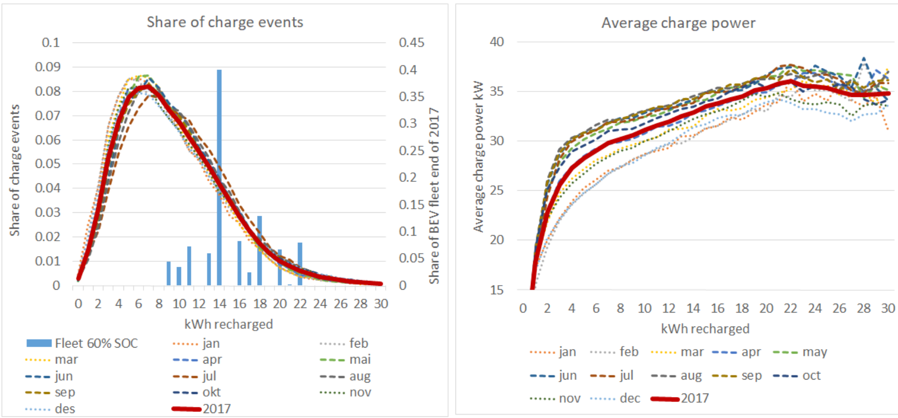


Figure 12: Share of charge events by kWh recharged per month with share of BEV fleet assuming 60% SOC fast charge window(left). Average charge power by kWh charged (right). 2017.

The effects of public holidays can be seen in the weekly plot of power, energy and time in figure 13. The charge power is higher in the summer than in the winter and holidays are seen as an increased energy charged in the summer vacation (week 28-30), and in the peaks in weeks 8 (winter holiday), 15 (Easter) and 40 (Fall holiday) for Oppland and Vestfold. Oppland is a typical winter vacation destination and a summer holiday corridor. Vestfold is a typical summer travel corridor. The average power is lower in Oppland in the summer holiday weeks than the weeks before and after indicating a battery heating effect in long distance high speed driving.

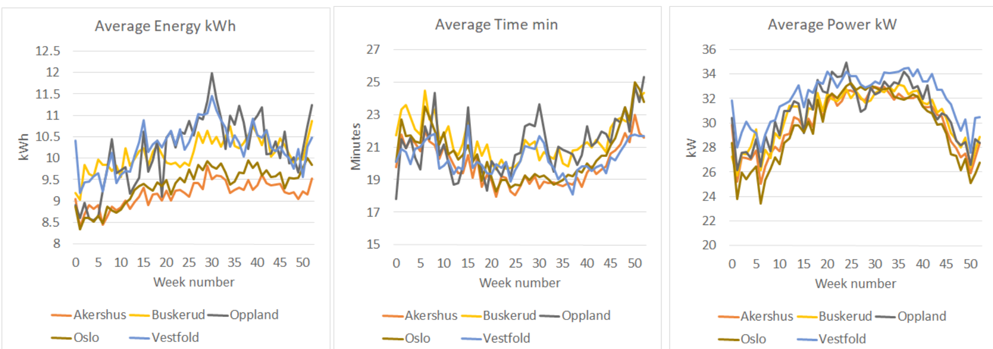


Figure 13: Average energy charged, time used and average power of fast charging in provinces in Norway in 2017.

4.3.3 Other factors that cause variability of use

Other factors also influence the fast charger process, such as the trip type. Local users likely only charge enough to get to their home base whereas long distance drivers need to charge enough to get to their destination. The latter are likely to charge more kWh than the former. The type of facilities at the charge stations also influence how long people stay. There is, for instance, a tendency for people to stay longer at shopping centres than other locations in both datasets.

5 Discussion

Fast charging is a complex socio-technical system. The analysis in this paper suggests that the following seven parameters play a large role in the user utility of fast charging:

1. User needs for charging and user driving and charging habits
2. The BEV fleets technical characteristics, i.e. battery size, fast charge capability
3. Energy charged (kWh) by each vehicle
4. Average charge power (kW) for each vehicle
5. Time spent charging (min) by each vehicle
6. Total volume of charging (min), i.e. the sum of the time all vehicles charge
7. Charge queues built up from the total charge volume and the time dimension

These parameters interact with each other and are influenced by a number of factors, as seen in figure 14.

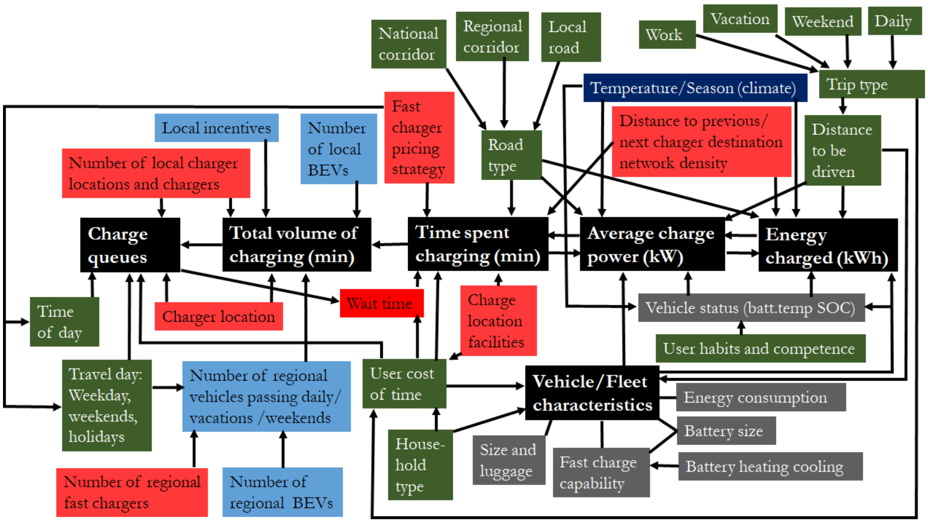


Figure 14. The fast charge landscape. Dark green are the user needs and habits that influence charging/vehicle choice. Black are the factors that determine the user interaction with, and perception of, fast charging infrastructure. Blue are factors influenced by the total fleet of BEVs and by political decisions. Red are factors influenced by fast charge operators. Grey are factors that cannot be influenced after the vehicles have entered the fleet. Source: Author.

Vehicle fleet characteristics are the most important factors. The household type influences the selection of vehicle, whilst the vehicle size and the cost of time will influence the type of trips the vehicle is used for. The fast charge capability depends heavily on the battery size and the battery heating and cooling system. Energy consumption varies with ambient temperature. Once the vehicle is in the fleet, these characteristics cannot be influenced. The distance from the start or the previous fast charge station, and the distance to be driven to the destination or to the next charging station determines not only the energy need, but also the fast charge power (as it influences SOC start and stop). It also depends on the trip type, where daily trips tend to be fairly short and vacation trips long. The road type influences the average speed of the vehicle which again influences the energy consumption and the charge power. The status of the vehicle when the charging starts depends on the type of vehicle, the ambient temperature, i.e. the variation in the energy consumption, and the user charging habits and competence. The time spent charging obviously is influenced by the energy needed and the fast charge power. Other factors are the cost of time, wait time, the attractiveness of the facilities at the station, as well as the pricing strategy of the operator. The total volume of charging is determined both by local users and vehicles passing through and the charger location, but also the network of fast chargers locally and regionally. Local incentives can enlarge local markets. Charge queues occur when to much of the volume of charging occur at the same time, mainly because of large variations in traffic over the day, the week or the year.

5.1 Charging into the future

More advanced battery thermal management systems and larger battery capacity will increase the fast charge capability of BEVs. The user experience will then improve and the infrastructure will be better utilized. Car manufacturers will install large battery packs because the marginal cost of enlarging a battery in a BEV is low [2]. These larger packs can be fast charged with higher power as they contain more active material. For larger vehicles battery pack sizes of 75-100 kWh seems to be standard, allowing fast charge rates of 100-150 kW. Porsche is so far the only manufacturer pursuing more than 150 kW for a production vehicle. Compact vehicles will typically get battery packs of 40-60 kWh that currently allow for 50-100 kW charging.

Charging networks can be made more dense so that it will be easier to charge the current generation of BEVs optimally on long distance trips. The charge power can be higher and charge queues can be reduced, if users charge withing the optimum SOC band. For longer range vehicles, the need for charging can be met by larger charger parks spaced further apart, at locations with stronger grid, thus lowering the grid costs. A network of 150-175 kW chargers (some are upgradeable to 350 kW) has been under deployment from the start of 2019.

Fast charge power may become as important for users as range. Figenbaum [2] found that a 40-50 kWh battery that can be charged with 100-150 kW power could be a good trade off between practicality, economy and ecology. The charge time will then be within time used for pauses on long distance trips. Manufacturing battery packs is energy intensive and cause emissions, depending on where they are manufactured. Users rarely need the full capacity. If the charge speed can be increased, it would reduce the need for a large battery. Measurement of the real fast charge speed at different ambient temperatures should become a mandatory type approval test.

5.2 Relevance for professional users and Heavy Duty Vehicle applications

CCS and Chademo chargers can be used by vans that are used by enterprises. Since roughly 3% of the BEV fleet is composed of vans, only a small share of the charging is for vans. The variation in charge power over the year will likely be the same for small vans as for BEVs as they have the same battery types and battery management systems. Nissan has, however, active cooling on the E-NV200 van. It will in Heavy Duty Vehicles (HDVs) be essential to keep the battery temperature optimum so that it can accept a high fast charge power. Fast charging is downtime in the working day of a professional user, due to the labour costs and loss of income. HDVs will likely have less range issues in the winter, being used more intensely over a day than a consumer BEVs. The intensive use keeps the battery temperature up in the winter but may in the summer lead to so high temperatures that the charge power will be reduced, unless managed properly by the battery cooling system.

6 Conclusion

The fundamental physical limitations of the fast charging capability of batteries as they are implemented in the vehicle with the associated thermal control systems, combined with the effects of climatic variation and variation in transport activity over the year, influence the way users fast charge, how much energy they charge, and in particular the achieved fast charge power. The achieved average power is much lower than the theoretical capability of the fast chargers, and the energy charged is lower than expected based on battery sizes in the fleet. The limitations of the battery thermal controls in the vehicles are the direct cause of these effects, which need to be taken into account when dimensioning fast charge networks.

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