


## CASE STUDY

# Anatomy of electric vehicle fast charging: Peak shaving through a battery energy storage—A case study from Oslo

Antti Rautiainen<sup>1</sup> | Kalle Rauma<sup>2</sup>  | Lena Rohde<sup>2</sup> | Antti Supponen<sup>1</sup> |  
Fabian Raulf<sup>2</sup> | Christian Rehtanz<sup>2</sup> | Pertti Järventausta<sup>1</sup>

<sup>1</sup>Unit of Electrical Engineering, Tampere University, Tampere, Finland

<sup>2</sup>Institute of Energy Systems, Energy Efficiency and Energy Economics, TU Dortmund University, Dortmund, Germany

## Correspondence

Kalle Rauma, Institute of Energy Systems, Energy Efficiency and Energy Economics, TU Dortmund University, Dortmund, Germany.  
Email: [kalle.rauma@tu-dortmund.de](mailto:kalle.rauma@tu-dortmund.de)

[Correction added on 09 December, after first online publication: Corresponding author's name has been changed from Rauma Kalle to Kalle Rauma in this version]

## Abstract

The number of electric vehicle (EV) users is strongly increasing so that today roughly every second registered vehicle in Norway is an EV. To increase the EV utilization, politics, industry and the EV users strongly promote the integration of fast charging infrastructure. While the future demand of fast charging sites is a well-studied topic, not much is known about the utilization of the existing charging sites and daily load curves. To fill this knowledge gap, usage data of a charging site in Oslo is analysed. Further on, the impact of a battery energy storage (BES) as well as a photovoltaic generator on peak load reduction is studied. The analysis shows variations and trends in the daily and weekly charging behaviour depending on the degree of utilization of the charging station. On average, a single EV user charges around 10 kWh in 19 min. Furthermore, the evidence indicates that EV users may have adapted fast charging as a part of their daily travels and it is not used only during long distance journeys. The results suggest that a BES can reduce the peak load by up to 55%. By adding a photovoltaic generator, a minor additional reduction of peak load is seen.

## 1 | INTRODUCTION

Globally, there is a strong need for transition to sustainable transportation system. The problems of today's transportation such as significant CO<sub>2</sub> emissions, air quality related emissions and oil dependency should be tackled. One of the needed solutions is electric transportation. Since the emerge of the electric vehicles (EV) at the beginning of this millennium, the number of EV users is strongly increasing, so that today for example, in Norway roughly every second registered vehicle is an EV [1]. Also, globally the amount of EVs is increasing rapidly. However, there are still some challenges for the EVs to become mainstream road transportation solution. One of the challenges is an insufficient charging infrastructure [2–5]. The fact is that still the charging of EVs is considerably slower than refuelling a traditional internal combustion engine (ICE) car. Fast charging stations, defined here as charging stations with maximum charging powers  $\geq 50$  kW, are therefore a necessity [6–9]. In a survey in 2017, executives from the automotive industry claimed that the integration of public fast charging networks is a precondition for the growth of the EV market

[10]. EV users state that they would prefer fast charging solutions for both intra urban and long distance travels compared with slow charging opportunities [11], especially for leisure travels [12]. Furthermore, the pure existence of fast charging sites reduces the range anxiety of EV user, which is one of the major concerns of possible EV users [13–15].

In Norway, not only the share of EVs is high but also the number of charging stations [16]. A high number of fast charging stations has effects on the local distribution grid, and it is necessary to understand how the real-life fast charging stations are used [17, 18]. Therefore, the paper focuses especially on the following questions:

- How often public fast charging stations are used?
- How long EV users charge and how much energy do they charge per charging event?
- How do load curves of fast charging sites look like?
- How much the highest peak of the charging curves can be decreased through the use of a battery energy storage (BES)?
- What is the impact of a photovoltaic generator on peak shaving?

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Authors. *IET Electrical Systems in Transportation* published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology.

In order to answer these questions, a comprehensive analysis of a measurement dataset covering a real fast charging site is conducted. The charging site, selected for this purpose, is located next to a highway in a suburban area of Oslo, which is one of the EV hot spots in the world.

The first major contribution of this paper is that it reveals how real fast charging sites are used. It is important to notice that the charging data is gathered at a fully commercial charging site that is not a prototype, a test facility or similar unique setting. The data we use in our paper includes also the information of charged energy. Thus, real charging behaviour can be observed. Such data cannot be obtained by any other means as accurately as through real-time measurements. Eventually, the charging is strongly dependent on the user behaviour and on how the customers use the EVs, which are difficult to be estimated.

The analysis using the real data helps in the electrical modelling of a fast charging site for further research. Understanding the charging behaviour in different locations helps to size and to design future charging sites more accurately. Valid real-life data helps to avoid under- or over-sizing of components.

Further in this paper, the impact of a stationary BES and a photovoltaic power generator on the peak shaving at the same charging site is analysed. The second major contribution of this paper is to analyse, how much a BES or/and a photovoltaic generator can help in peak shaving of a real fast charging site. The peak shaving is carried out so that the charging power of the EVs are not decreased. Peak load management is important due to the fact that the components must be sized according to the peak load. On one hand, the queuing time of the customers due to reduced charging power cannot be very long. On the other hand, oversizing the components result in redundant capacity and elevated costs. Thus, a compromise between these two extremes should be found.

Even if the optimization methods used in the operation of a BES in this work are not new itself, the combination with relevant real-world data distinguishes the paper from most other research works.

In reality, the decision whether a BES is installed at a charging site is based on the economic feasibility, the paper does not focus on the economic factors. The economic variables are strongly project- and location-dependent. However, the focus on this paper is on the technical feasibility and the economic efficiency is left for future work.

The paper is organized as follows. Related state-of-the-art is presented in Section 2. In Section 3, the used fast charging data with the main analysing methodology are introduced. In Section 4, the results of the analysis are presented and discussed. In Section 5 conclusions are made and future work is proposed.

## 2 | RELATED RESEARCH WORKS

Fast charging station usage and profiles have been studied using many different approaches. Previous papers use the following approach/data: The number of cars on the road [19], current usage of gas stations [20], questionnaire [21],

commuters using fast charging station [22], prediction of number of people forgetting to charge overnight [23], internal combustion engine (ICE) driving data [6, 24] and utilization of existing DC charging sites [6, 25]. In most of these studies, real fast charging data is not used, and in the ones that contain real data, do not have information on charged energy.

Peak shaving through EV charging is a topic widely addressed in academic studies. In the study presented in [26], three simulated charging sites with different power capacities are compared. The EV charging data used in the study is synthetic and based on measured traffic data that is further used to form different use scenarios of the charging sites. The study compares three simulated charging sites with different power capacities. The largest charging site has 12 fast charging points with the nominal power of 150 kW at each charging station. This results in the maximum peak power of 607 kW with an average use rate of the charging points of 31%. The results of this study can be used to validate the theoretical findings of the study in [26].

The study in [27], has the objective of reducing the peak power of a fast charging site through the use of a stationary BES. An interesting add of this work is to take into consideration the impact of the bottleneck stemming from the lack of power capacity from the network (resulting in longer charging and times) on queuing times. This study considers a charging site with eight 120 kW chargers and a stationary BES with the capacity of 1000 kWh, that is significantly larger than in this paper. Real EV charging data is not used, but modelled data based on studies from gasoline vehicles. The result show that in the best case, the size of the grid connection can be reduced from 1800 to 500 kW by using a BES of 1000 kWh.

The work presented in [28] has its focus on designing a fast charging site with BES and a photovoltaic generator. The study [29] poses a similar objective, but additionally a diesel generator is integrated at the charging site. The design of the station is based on economic factors. Real EV charging data is not used.

In [30], the impact of a BES on a high-power charging site with five charging stations site over one day is analysed. Each charging station has the nominal capacity of 150 kW and the capacity of the BES is selected as 437 kWh. The peak power drawn from the power grid is decreased by about 30% through the use of the BES. The study is based on a simulated scenario in Copenhagen.

The work in [31] is focused on the development of an energy management system for a grid-connected fast charging site consisting of six charging points, a photovoltaic generator, a BES and a fuel cell. In this case, a real charging data of EVs is not used. The work does not focus on peak shaving, but rather on analysing the costs of the charging site for the next 25 years. The outcome of the work supporting this paper is that the economic performance of such charging site with generation capabilities seem positive in the light of current predictions of the future. The study [32] analyses the economic impact of BES and a photovoltaic generator on a fast charging site in Canada. The major outcome is that the addition of such components can result economically feasible in five to ten years' time due to the decline of the component prices. The

work states that there may be reasonable differences in the payback times between cities due to differences in the electricity rates. In this case, no real EV charging data is used.

The simulations in [33] demonstrate that a fast charging site together with a BES and photovoltaic and wind power generation can be economically feasible. The simulated charging sites had four to five fast chargers and a maximum BES capacity of around 380 kWh. Even if the charging data is simulated, the study presents a solid strategy to estimate the overall economic feasibility of such a charging site. The case is focused on Spain, but the methodology could be extended to Norway to broaden this paper.

In [34], a new energy management system with an integrated BES, a photovoltaic generator and an EV with fast-charging (CHAdeMO) capability is designed. The study focuses on the experimental development on one to two EVs. Even though the study focuses on more power electronics and on the experimental application, it provides a complementary work to this paper.

The literature reviews show that not much research is based on actual charging data. This paper will support the future research by providing insights of the charging behaviour at real fast charging site. In turn, this will improve the EV charging models of future studies.

### 3 | METHODOLOGY

This section is divided into two parts. In the first sub-section, the methodology to analyse the real charging data is presented. In the following two sub-sections, it is shown, how the impact of a BES-only and BES and a photovoltaic generator at the charging site is evaluated, respectively.

#### 3.1 | Analysis of the charging data

The case study consists of a charging site located next to a highway in a suburban area of Oslo, combining the two major use cases for fast charging sites: Everyday charging and charging for long distance trips. Norway and especially Oslo has a very high number of EVs. In 2017, Oslo had the highest ratio of cumulative EV with around 40,000 per one million inhabitants and around 53,000 EVs in the wider Oslo area. At the same time, it has the third highest ratio for EVs per fast charging port/connector, following the two Californian cities San Jose and Los Angeles. [35].

The original dataset of the case study of this paper is kindly provided by *Fortum Charge & Drive*. Data consists of 32,920 charging events from the period of 22 May 2018–31 December 2018 (224 operation days). The data comprises the following information for each of the charging events.

- Start time
- Stop time
- Charged energy (in kWh) and
- Type of the used connector

In the data, the charged energy for some events is very low, indicating probably a technical error or a user-related incident. At the same time there are events with a very long duration or an unreasonably high charged energy, indicating different communication/software errors. Therefore, the data set is filtered by leaving out all charging events with:

- A consumed energy less than 0.1 kWh
- An incomplete data set (start time, end time or consumption)
- All charging events lasting longer than three hours and
- All charging events consuming more than 100 kWh

After this filtering, some further processing of the dataset is made. All charging events that extend over two days that is begin before midnight and end after midnight, are divided. This step is necessary, as our data processing algorithm simulates day by day based on the starting time of charging events. Therefore, the charging processes after midnight would be neglected, without dividing the events into two separate events, one lasting until midnight and the second starting just after midnight on the next day. After using these filters a data set of 30,722 charging events remains, which is 93.3% of the original data set.

The charging site consists of ten 50 kW DC charging stations with CHAdeMO and CCS connectors. Eight are in service from the beginning of the period and two additional charging stations are installed in October. The first charging event collected from the two additional charging stations to the backend system is on the 1 November 2018.

One of the aims of the case study is to assess the load profiles of the individual charging stations and the charging site. The dataset provides start time, end time and the charged energy during the charging event and not for example, the type of the car or the behaviour of the charging power during the charging process. In order to assess the load profile, some assumptions must to be made. Based on [36], it is assumed that during the first 60 s of the charging event the power is ramped up to the maximum value and after that, the power is constant until the end of the charging. If the charging time is long and/or the battery is near full state in the beginning of the charging process, the charging power starts to decrease when the state-of-charge (SOC) of the battery approaches full state. The maximum power assumed in the calculations is the average power during the charging event, as we do not have more detailed information on the behaviour of the charging power.

A fact supporting the chosen approach is that the pricing method at the charging site is time-based: The more time a customer occupies a charging station, the more expensive is the charging for the customer. Most EV have a charging profile with a decreasing power curve at the end of the charging process. Thus, the customers pay more per kWh at the end of the charging process than at the beginning of the charging process. Because of this, it is possible that some customers prefer not to charge the battery completely. In this way, the charging profiles of their vehicles remain relatively flat.

The selected approach leads to rather conservative maximum power values of individual charging stations together with conservative resulting power values for the whole charging site. On the charging site level, the result is less conservative, as the proportional peak of the sum of multiple random charging profiles decreases as the number of charging profiles increases (transposition phenomenon). Also, when the charging is carried out at the SOC levels clearly  $< 100\%$ , the constant charging profile assumption is rather justified. The dataset supports this assumption as the large majority of charging events consume less than 15 kWh (82%) and for these events is a power drop unlikely. The lack of information about the charged EVs makes it hard to estimate suitable charging profiles, as the profiles depend on many non-observed parameters like the temperature of the battery.

### 3.2 | Impact of a battery energy storage

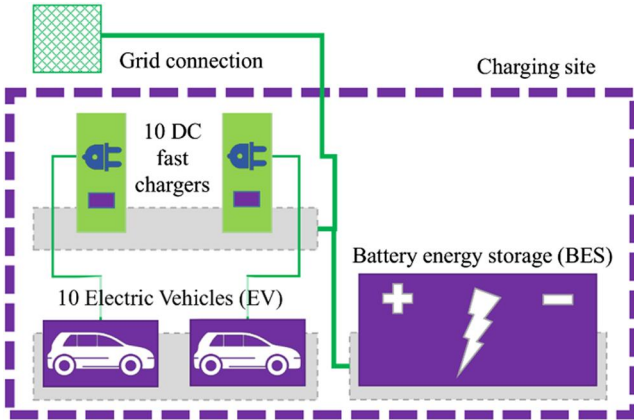
In this subsection, it is explained how a simulated BES is integrated at the charging site and how its impact on peak shaving is computed. A simplified illustration of the charging site is shown in Figure 1.

The purpose of the battery is to decrease the peak load at the charging site by shifting a part of the load from the peak to the valley times. The charging sessions of the EVs remain unaffected. The optimization problem is formed by using quadratic programming, where the objective function is quadratic and the boundary conditions are linear.

The objective function  $f(x)$  is minimized and is presented in (1) as

$$f(x) = \sum_{i=1}^N ((P_{BES}(i) + P_{EVload}(i))^2, \forall i \in [1, N]), \quad (1)$$

where  $x(i)$  is equal to the power charged and discharged from the BES at every time step  $i$ . The powers are used because to easier distinguish the highest peaks.  $P_{EVload}$  is the modelled charging power of an EV based on the real charging data [33].



**FIGURE 1** Illustration of the charging site together with a BES. BES, battery energy storage.

The output of the optimization is the charging or discharging power of the BES, where  $N = \frac{24h}{\tau}$ , in where  $\tau$  is the resolutions of the simulation time.

The inequality constraints presented in (2) are linear. The SoC of the BES must stay between the limits of the minimum and the maximum values,  $SoC_{BES,min}$  and  $SoC_{BES,max}$ , respectively.  $SoC_{BES,init}(i)$  is the initial SoC of the BES and varies at every time step.  $Q_{BES}$  is the capacity of the BES and  $P_{BES}(i)$  is the output power of the BES. The SoC of the BES cannot exceed 100%. Additionally, the minimum SoC cannot be lower than the selected minimum SoC that is set by the user before running the algorithm. The inequality constraints are

$$SoC_{BES,max} \geq SoC_{BES,init}(i) + \tau \times \frac{\sum_{i=1}^N P_{BES}(i)}{Q_{BES}} \quad (2)$$

$$SoC_{BES,min} \leq SoC_{BES,init}(i) + \tau \times \frac{\sum_{i=1}^N P_{BES}(i)}{Q_{BES}}$$

In order to have energy reserve for the next day, the SoC of the BES must be the same at the beginning of the day as at the end of it [37]. This is used as a reserve capacity to guarantee that the BES has enough energy to respond a peak load even at the beginning of the day. This reserve capacity is defined by the user and in this study it is selected as 33% of the maximum capacity. At any time step  $i$ , the power charged or discharged by the BES must respect

$$x(i) \leq P_{BES,max} \text{ and } (i) \geq P_{BES,min} \quad (3)$$

Meaning that the power drawn from the BES must stay within the physical limitations between the maximum and the minimum power capacity of the BES. In order to solve the optimization problem, sequential least squares programming is used. More complete information of the methodology and the calculations can be found in [37].

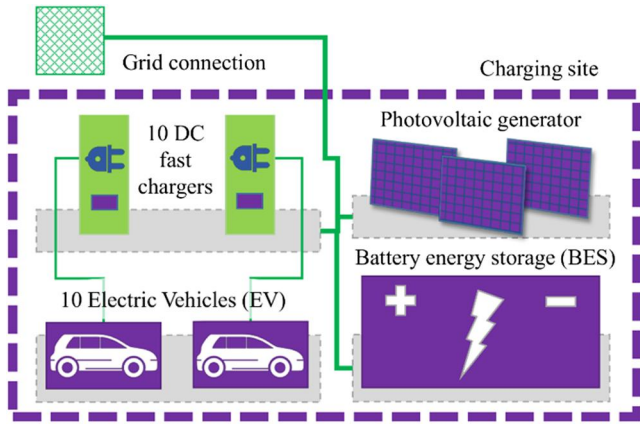
### 3.3 | Impact of a battery energy storage and a photovoltaic generator

This subsection describes the simulations of a BES and a photovoltaic generator at the charging site. A schematic illustration of the setup can be seen in Figure 2.

First, the objective functions are explained, followed by the boundaries and constraints. After that, it is explained how the solar irradiance is modelled.

The objective function (1) is modified to integrate the photovoltaic generator as

$$f(x) = \sum_{i=1}^N ((P_{BES}(i) + P_{EVload}(i) + P_{PVgen}(i))^2, \forall i \in [1, N]), \quad (4)$$



**FIGURE 2** Illustration of the charging site equipped with a BES and a photovoltaic generator. BES, battery energy storage.

$P_{PV_{gen}}$  is the power generated by the photovoltaic generator. This is obtained by the irradiance model explained at the end of this subsection.

The first two inequality constraints are the same as in (2). Two constraints are included to ensure that the SoC is always between 20% and 80% of its maximum capacity at the end of each day. The constraints are

$$\begin{aligned} SoC_{BES,max} &\geq SoC_{BES,init}(i) + \tau \times \frac{\sum_{i=1}^N P_{BES}(i)}{Q_{BES}} \\ SoC_{BES,min} &\leq SoC_{BES,init}(i) + \tau \times \frac{\sum_{i=1}^N P_{BES}(i)}{Q_{BES}} \quad (5) \\ SoC_{BES,d}(N) &\leq Q_{BES,max} \times 0.8 \\ SoC_{BES,d}(N) &\leq Q_{BES,max} \times 0.2 \end{aligned}$$

The solar irradiation is modelled as an ideal case with a Gaussian function, so that clouds, shadows, reflections or other disturbances are not taken into account.

$$f(x) = \frac{p}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-\mu}{\sigma} \right)^2},$$

where  $\mu$  is calculated

$$\mu = t_{sunrise} + \frac{t_{sunset} - t_{sunrise}}{2} \quad (6)$$

The time of the sunset and the sunrise are from Oslo in 2018 [37]. The factor  $p$  corresponds the seasonal variations in the irradiation. The irradiation is divided in four seasons. The used factors are listed in Table 1. Even if this paper studies the

impact of a photovoltaic generator during August (summer), the values of other seasons are listed for comparison.

## 4 | RESULTS AND DISCUSSION

Analogically with the previous section, first the results and discussion of the analysis of the charging data are presented. This is followed by the results and discussion about the impact of a BES-only as well as a BES and a photovoltaic generator on peak shaving, both in their own sub-sections. It is crucial to underline that the data at the same fast charging site is used through the paper.

### 4.1 | Analysis of the charging data

In this section, multiple different results are presented from different viewpoints in order to piece by piece answer the research questions presented in Introduction.

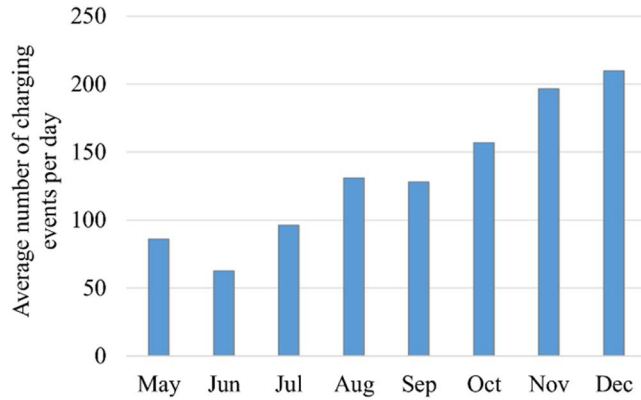
Figure 3 shows the number of charging events per day for each of the months May–December. One can see that there is a significant increasing trend during the study period. This is probably partly due to the increasing number of EVs in Norway and especially in Oslo. It can be seen that at the end of year 2018, the site had 210 charging events per day, which means 21 charging events per charging station. That can be considered quite a high number. There is a strong increase in the number of charging events between October and November. Believable, this is a sum of several causes, and some of the probable ones are the following:

- Installation of two additional charging stations at the charging site in November
- EV users are adapting their behaviour and are familiarizing themselves to charge at a DC charging site (habituation of the use of fast charging station)
- Some EV users are preferring DC fast charging over other charging opportunities
- Increasing number of EV users [38]
- During December and November the colder temperatures also reduce the battery capacity of the EVs, as cold decrease temperatures the operating voltage and the capacity [39]. This will make it necessary to charge more frequently, if the driving behaviour and distance travelled is the same in the winter and in the summer
- There may be other reasons, such as a road construction during the summer months, increased publicity from the charging operator or decreased use of bicycle and public transport (i.e. seen in the increased use of car) during the cold months

For such charging dataset, it would be interesting to analyse the seasonal changes/cycles of the charging need, but in this case, it is hard as there is an increasing trend in the utilization, and the seasonal variations are at least partly hidden under the

Season	Average solar irradiation (kWh/m <sup>2</sup> /day)	Factor $p$	Variance $\sigma$
Spring	3.7	0.67	7
Summer	5.5	1	10
Autumn	4.1	0.75	7
Winter	1.4	0.25	4.3

**TABLE 1** The factors used in the solar irradiation model

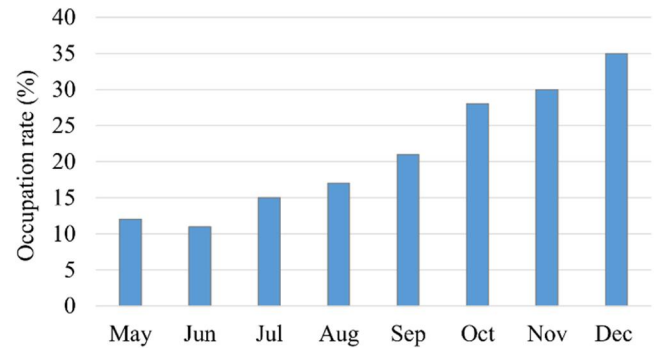


**FIGURE 3** Average number of charging events per day in different months

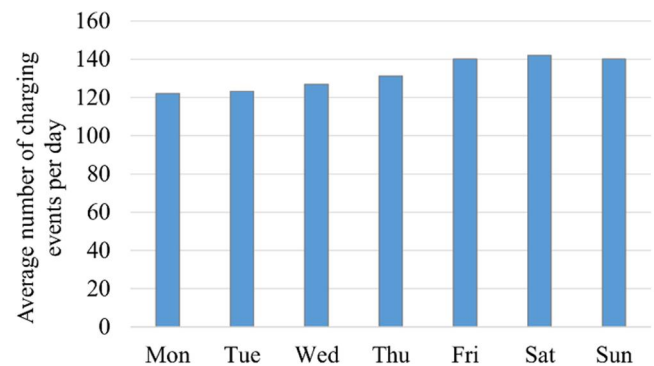
growth of the utilization rates. Figure 2 shows the average occupation rate of the charging stations over different months. The occupation level has increased from 11% in June to 35% in December. This means that in December, the charging station was in use 35% of time corresponding to 8 h 24 min per day on average. Such rate is very high and clearly indicated queuing at the charging site [6]. Moreover, it shows that the offer for fast charging stations does not match with the demand.

The data shows also differences in the utilization of the charging station between different day types (Figure 4). Figure 5 presents the average number of charging events per day in different days of week considering all the charging events from the whole data period. Saturday has the highest number of charging events per day, and the numbers of Friday and Sunday are very close to each other.

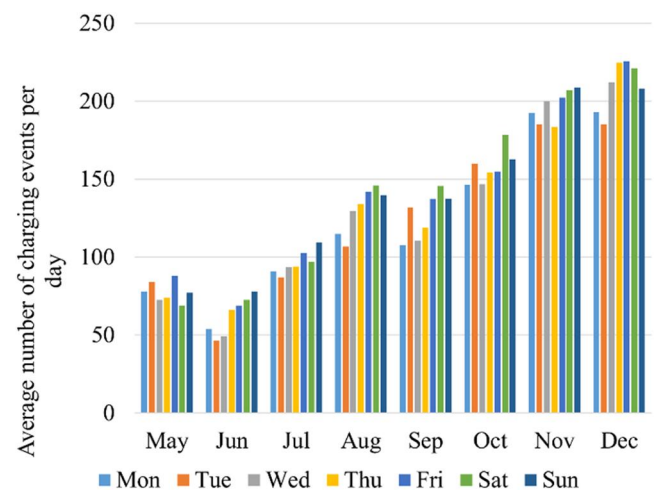
If the differences between the weekdays is considered on a monthly basis, certain trends can be observed. Figure 6 presents monthly average numbers of charging events per day in different days of week (Figure 7). The numbers of charging events in different weekdays varies month by month. Presumably, in many cases, long distance travelling happens relatively more often during weekends, and therefore it is beneficial to compare between two day types: Working days (Monday–Friday) and weekends (Saturday–Sunday). Figures 5 and 6 present only these two day types. In Figure 5, the average numbers of charging events per day of the two different day types are presented. In Figure 8, monthly ratios between the numbers of events in certain day type and the total number of events together with fitted lines are presented. What can be seen from the figures, and especially from Figure 8 is that over time, charging during working days is proportionally increasing compared with the weekend charging, although the weekend



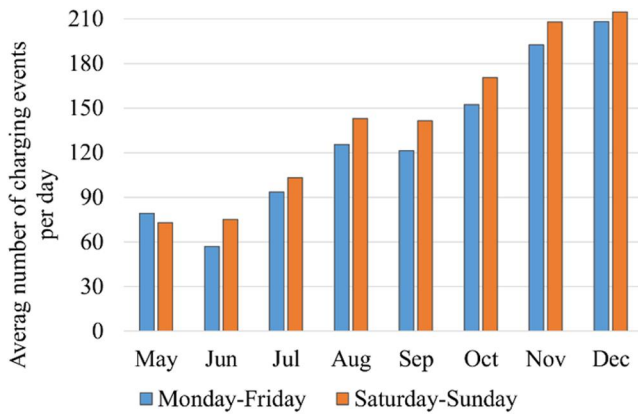
**FIGURE 4** Occupation rate in different months



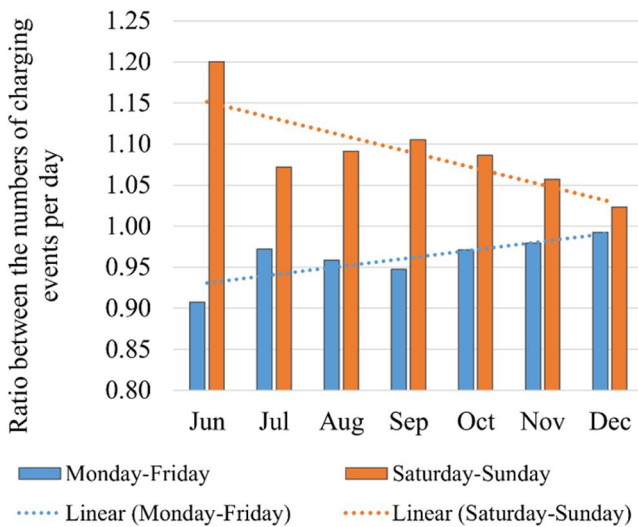
**FIGURE 5** Average number of charging events per day in different days of week



**FIGURE 6** Average number of charging events per day in different days of week



**FIGURE 7** Average number of charging events per day in two different day types: Working days (Monday–Friday) and weekends (Saturday–Sunday)



**FIGURE 8** For each month, the ratio of the two measures: Average charging events per day of a certain day type and the average total number of charging events per day

charging stays more popular until the end of the year. There are several possible reasons for this. One is that people who have satisfying home charging opportunities might purchase and start using EVs first [40], meaning that when EVs become more popular, also the need for fast charging increases. Another possible explanation is that when the outdoor temperature is low (in winter), EVs consumes more energy per kilometre, which means that there might be more need for fast charging also for the daily trips during working days. In addition, when it is cold, the range anxiety might become worse and people charge their EVs on a daily basis more in order to minimize the possibility to run out of power during a trip. An additional reason for the relative increase of charging during the weekdays could be the queueing at the charging site. Some customers might start a habit of charging during the weekdays in order to avoid the queues during the weekends.

Charging duration is a crucial measure. The shorter the visit at the fast charging station, the more competitive

choice EV is for the ICE car. Figure 9 presents monthly average charging durations. It can be seen that durations increase at the end of the year. One possible reason for this is that during the winter, EVs consume more energy and there is need to charge more energy, which takes more time. The average duration of all months is about 19 min. Figure 10 presents the monthly average charging energies per charging event. The average charging energy is about 10 kWh. One can see that amounts of energy charged are higher at the end of the year than in the summer. However, there is no clear correlation between the charging durations and charging energies at the end of the year. The charging durations grow quite linearly between September–December, but the corresponding charging energies do not grow in the same fashion. The reason for this very probably related to the outdoor temperatures, and this is illustrated in Figure 11. The figure presents the daily average charging powers during the charging events and the daily average outdoor temperature in Oslo. When the temperature of a lithium-ion battery with a graphite negative electrode (which represent the great majority of all Li-ion batteries) is low, high charging power cannot be used, and when the temperature is very low, charging should not be made at all [41]. This is because during charging at low temperatures, the lithium-ions do not necessarily intercalate into the negative electrode, but deposit as metallic lithium on the surface of the negative electrode decreasing the lifetime of the battery and decreasing the safety [42]. Therefore, low outdoor temperature tends to decrease the charging powers due to the control actions by the battery management system of the EV [43, 44]. Figure 11 illustrates a clear positive correlation between the charging power and the outdoor temperature. The Pearson's correlation coefficient between these two variables is 0.88, which implies a strong linear correlation. The correlation is statistically significant ( $p < 0.05$ ) (Figure 12).

Figure 10 presents the average load curves for different months based on the calculation method presented in Section 2. A load curve means here a time series of 15 min average powers of the whole charging site over a day. The increasing amount of charging events over the months can be clearly seen in the load curves as increasing load levels over the months. The charging is carried out only little around 3:00 AM–6:00 AM, but after that the charging curves start to rise fairly linearly. At around 14 h, the curves stabilize to quite steady levels for a few hours. June was an exception, as the growth started to stabilize around hour 12. After quite steady levels, the load curves begin to drop during the evenings and nights. The load curves are in surprisingly high levels at midnight and even a couple of hours after. Figure 13 presents the load curves for working days and weekend days covering all months. It can be seen that during weekends, the peak is a bit earlier than on working days and in the late evening and night charging is carried out later than during workdays. The maximum power of the individual 15 min periods over the whole dataset was 290 kW (this cannot be seen in Figure 10), which is 29 kW/charging station on average.

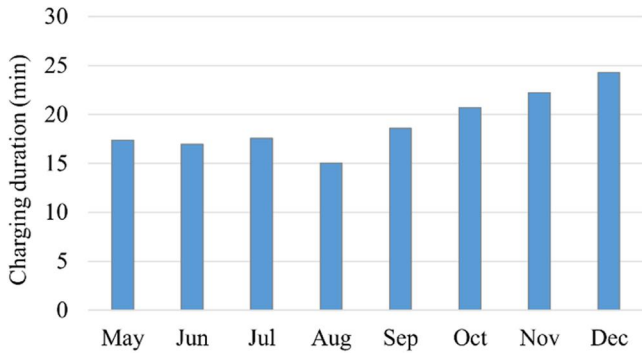


FIGURE 9 Monthly average charging durations

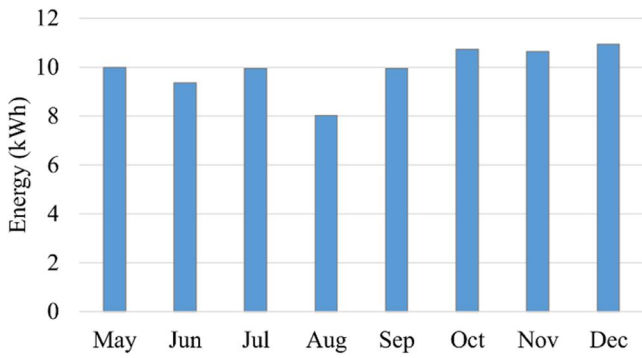


FIGURE 10 Monthly average charged energies per charging event

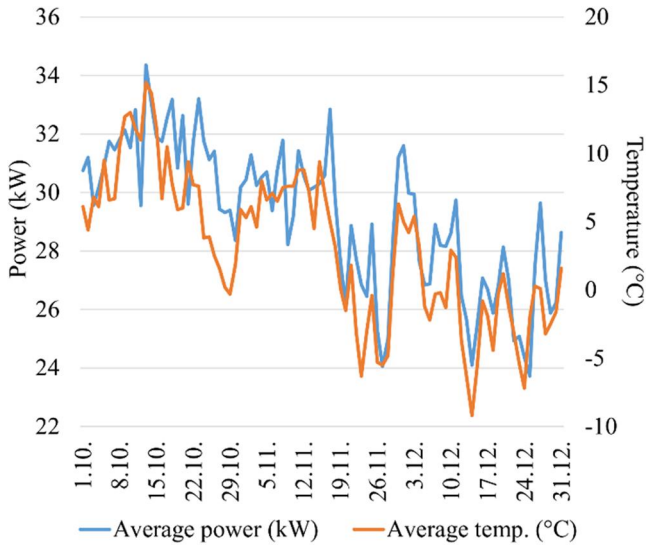


FIGURE 11 Daily average charging power of the charging events and the daily average outdoor temperature at the charging site

The distribution of charged energies according to the share of customers is seen in Figure 14. It shows how the charged energies are distributed between the charging events. It is clearly visible that most customers charge around 10 kWh although the distribution is quite broad.

Table 2 aggregates the key numerical values of the results.

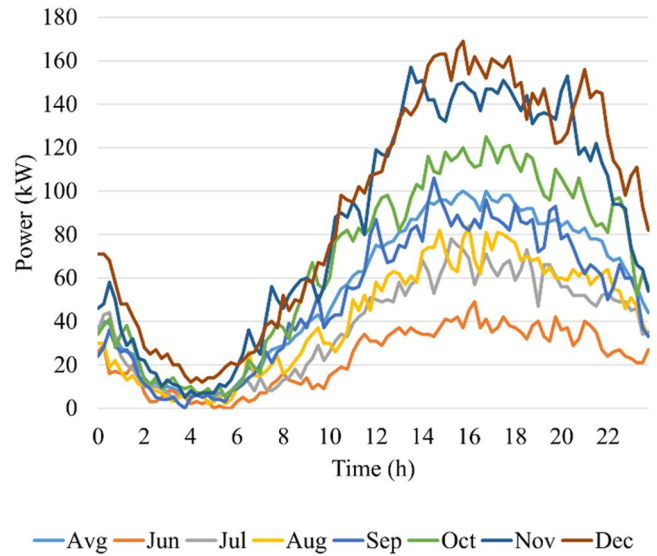


FIGURE 12 Average total power of the charging site in different months

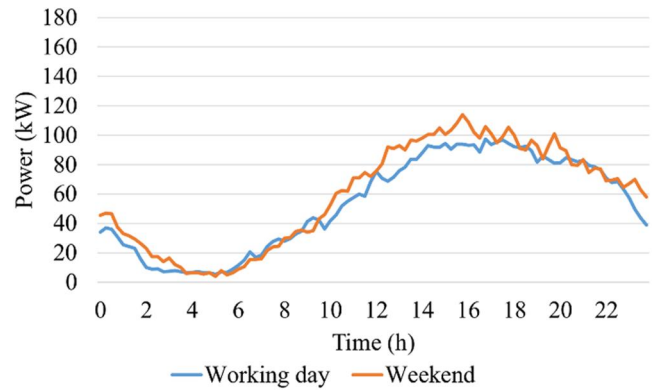


FIGURE 13 Average total power of the charging site in working days and weekend days

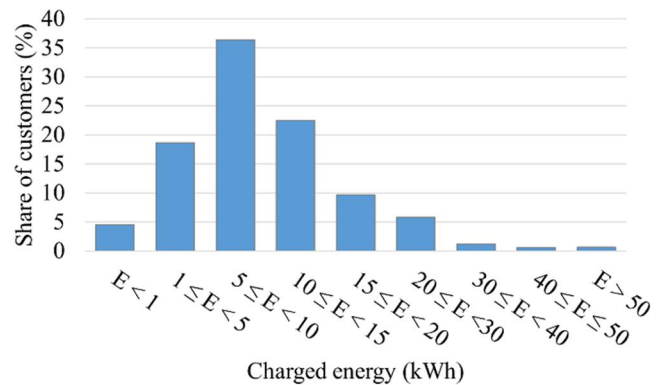


FIGURE 14 Distribution of the charged energies according to the share of customers

## 4.2 | Impact of a battery energy storage

As seen in the results through Section 4.1, each month has slightly different charging characteristics.



**TABLE 2** The key characteristics of the charging site

Quantity	
Number of the charging events	30,722
Average charged energy per charging event	10 kWh
Total amount of charged energy over the whole data timespan	307 MWh
Average charging duration	19 min
Average occupation rate of the charging stations	21% (scale of 11%–35% between different months)
Peak power of the charging site	290 kW (29 kW/charging station on average), (58% of max. Power output)

That is why, it is useful to analyse the performance of the BES during different months. In this section, the impact of a BES on peak shaving during August and December are compared. An overview of the arrangement is visible in Figure 1.

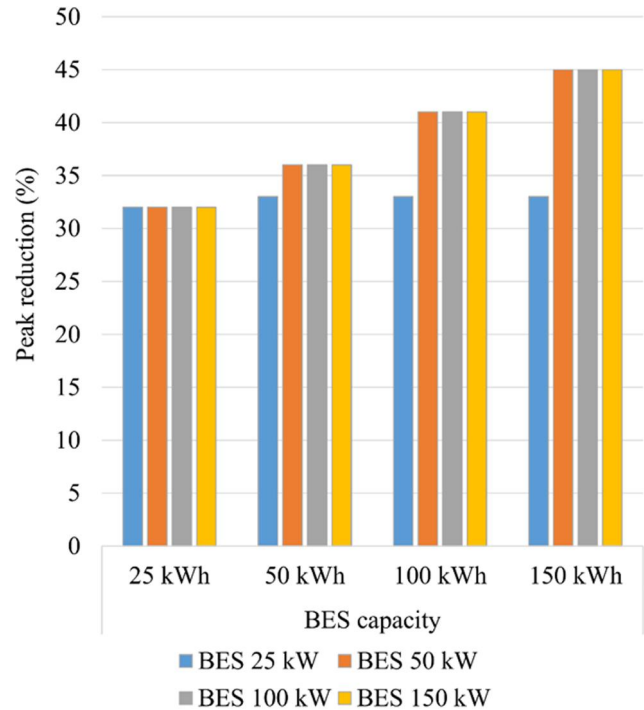
Figure 15, illustrates the average peak reduction during August. The outcomes of the simulations by using BESs with four different power capacities (25, 50, 100 and 150 kW) and four different energy capacities (25, 50, 100 and 150 kWh) are shown.

It can be noted in Figure 15 that the BES with the lowest nominal power and energy ratings (25 kW/25 kWh) provides an average peak reduction of 32% during August. The figure further illustrates that by increasing the energy capacity and maintaining the power capacity at 25 kW, improves the performance only minimally. The best performance is achieved with a BES rated with 50–150 kW and 150 kWh. In that case, the average peak reduction is 45%.

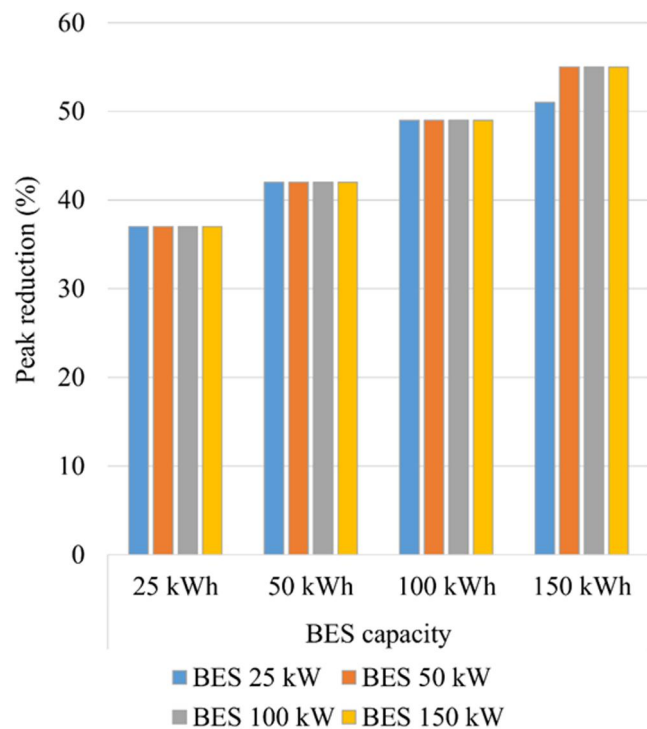
Analogous results are presented for December are presented in Figure 16. Logically, the lowest peak reduction is 37%, with a BES of 25 kW/25 kWh. The highest peak reduction with the highest-rated BES is 55%.

As each month poses slightly different charging characteristics, the ability of a BES to assist in peak shaving varies monthly. Reasonably, both curves are characterized by similar shapes simply meaning that a larger BES is able to reduce the power peaks more efficiently. It should be kept in mind that the figures are not directly comparable since both months have different power peaks. Most importantly, Figures 15 and 16 reveal a fair estimation about the order of magnitude that can be expected when a BES is installed at the charging site.

Losses of the BESs are dependent on the battery technology and, as previously mentioned, the losses of the batteries are not considered in this study. Including the losses will further reduce the efficiency of the BESs. Although this paper does not focus on optimizing the battery lifetime, such considerations are important to be taken into account in the future. The optimization presents the best possible scenario in the sense that the arrival of EVs can be forecasted. In a real installation this would not be the case, which decrease the performance of the BES in peak shaving. However, the study



**FIGURE 15** Average peak reduction at the charging site with different sized of BESs during the month of August. BESs with four different output powers and two different energy capacities are used. BES, battery energy storage



**FIGURE 16** Average peak reduction at the charging site with different sized of BESs during the month of December. BESs with four different output powers and two different energy capacities are used. BES, battery energy storage.

shows the limits of performance that can be achieved in the best case.

Finally, the decisions whether to install a BES or not and what kind of BES to install, are determined by economic factors. Within the scope of this study, it is demonstrated that even a BES with relatively low electrical dimensions (25 kW/25 kWh) has a significant impact on the average peak reduction. This shows that a BES could provide an economically feasible alternative for a larger connection size between the public power distribution network and the charging site.

### 4.3 | Impact of a battery energy storage and a photovoltaic generator

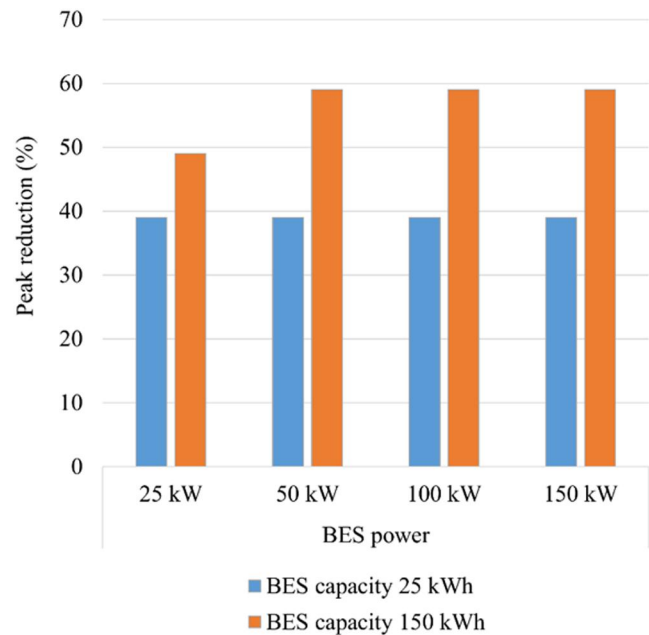
In this section, the results and the analysis of peak shaving by using a BES and a photovoltaic generator are carried out. An overview of the setup is illustrated in Figure 2. The results of August with two different sizes of photovoltaic generators, 20 and 40 kW, are compared with each other in order to see the impact of a photovoltaic generator on peak shaving. The month of August is selected since it is a summer month. Oslo is located in a relatively north, with long summer days and short winter days. Therefore, the impact of a photovoltaic generator during winter time is expected to be minimum and thus excluded from the study. The results of the BES with the smallest (25 kWh) and the largest (150 kWh) energy capacities are considered.

The average peak reduction in August can be seen in Figure 17 in the case of a 20 kW photovoltaic generator. Figure 18 illustrates the results of the same study, but for a photovoltaic generator with 40 kW nominal power. The results of Figures 17 and 18 are comparable with the results presented in Figure 15.

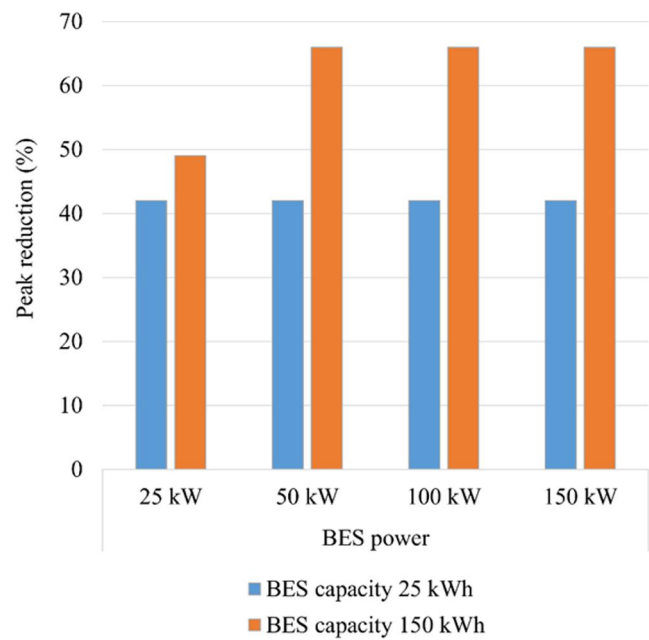
In Figure 17, it is visible that with a BES of 25 kWh, the peak reduction is 39% in all studied power ratings. Thus, installing a BES with a more output power does not increase the performance. Without a photovoltaic generator, the peak reduction would be 37%. On the other hand, if the BES has an energy capacity of 150 kWh, then a power output of 50 kW provides an improved average peak reduction of 59%. The same case without a photovoltaic generator is 55%. It can be concluded that investing an output power more than 50 kW in a BES may not be economically feasible.

Figure 18 shows a similar shape that can be seen in Figure 17, but with higher values. Comparison of Figures 17 and 18 illustrates that stronger solar irradiation has a beneficial effect on peak shaving. This shows the contribution of increased solar capacity in peak shaving. With the smallest BES rating (25 kW/25 kWh), the peak reduction increases marginally from 39% to 42% when the photovoltaic generator is upgraded from 20 to 40 kW. With a larger BES (50 kW/150 kWh), the average peak decrease improves from 59% to 66%.

The results show that a photovoltaic generator has only a minor impact on peak shaving at the fast charging site. However, it will reduce the overall energy drawn from the



**FIGURE 17** Average peak reduction at the charging site when a photovoltaic generator of 20 kW is used during the month of August. BESs with four different powers and two different energy capacities are used. BES, battery energy storage.



**FIGURE 18** Average peak reduction at the charging site when a photovoltaic generator of 40 kW is used during the month of August. BESs with four different output powers and two different energy capacities are used. BES, battery energy storage.

distribution grid, especially during the long summer days. The result is reasonable considering the size of the photovoltaic generator. In this analysis, clouds, shadows or other factors reducing the solar irradiation on the panels are not considered. In reality, such factors further decrease the performance of the photovoltaic generator. Installing a larger photovoltaic

generator would improve the performance. However, it should be considered that in practical applications, especially in urban areas, the lack of physical area exposed to direct sunlight may be a limiting factor.

## 5 | CONCLUSION AND FUTURE WORK

In this section, the main conclusions and ideas for future research are presented.

### 5.1 | CONCLUSION

Electric road transportation has been in the spotlight for a few recent years as an alternative for its fossil rival. EV have to be charged from a power source, typically from an electricity grid. EV fast charging is a necessity for successful deployment of EVs, and therefore it is necessary to understand the impacts of fast charging stations on the electricity grid and on the transportation system.

In this paper, data from highly used EV fast charging site comprising 10 DC fast charging stations in Oslo was analysed. The aim was to understand how real EV fast charging stations are used. The data is valuable especially due to the fact that it is measured at a commercial charging site, which is not a unique setting only for research purposes. Thus the results reflect the real user behaviour. The results imply that the stations are used frequently in every day of week, but in the weekends, charging seems to be made a bit more than in the working days. This difference, however, decreases over time in the dataset of this paper. Charging stations were used also broadly within the days. Only a few weekly hours had very low usage. Also, a significant temperature dependency in the charging rate was observed; the colder the weather, the slower the charging. Seasonal variations could not be observed from the data, as the dataset covered 224 consecutive days. Also, the number of EVs in Oslo (also in the world) increases rapidly, and this makes it hard to observe seasonal utilization cycles, because the seasonal variations are at least partly hidden under the growth of the utilization rates.

A BES increases the flexibility of the charging site notably, which leads to fact that more customers can be served with a smaller grid connection capacity. A BES can decrease the peak load at the charging site significantly. The highest decrease of the peak load by 55% is achieved by using a BES with 150 kWh energy capacity. Generally speaking, the higher the energy capacity of the BES, the more peak load can be reduced. Incorporating a large photovoltaic generator in the charging site, a reduction of the peak load by 66% is reached in an ideal case. This paper does not consider the economic aspect, but it indicates that incorporating a BES at a charging site could be a technically sound alternative to a network reinforcement. Generally, it can be said that the findings of this paper point to the same direction as the results found in the scientific literature. Considering that the simulations are based on real charging data, this paper provides a meaningful

contribution in the research carried out in the field of EV-power system integration.

### 5.2 | Future work

The study raised several further questions and research needs. One is that more data of different types of charging sites should be analysed. This is necessary for understanding the seasonal variations and the impact of the physical location of the charging site. This could be approached by using clustering techniques. Presumably, city centre charging stations are used differently than ones, which are mostly used near the highways to enable long distance EV travelling. In addition, the data should include more information about the charging. For example, the information on the behaviour of the charging power during the charging events would be valuable.

The optimization strategy will be further developed by testing non-linear approaches. Real-life applications of predictive BES control will be developed. Also, economic and ecologic factors and losses of the BES options will be analysed in the future. In addition, ways to improve the accuracy of the charging profiles of individual EVs will be included in the future research.

### ACKNOWLEDGMENTS

The authors would like to thank Fortum Charge & Drive for providing data for the work. The work was partly supported by the German Federal Ministry of Transport and Digital Infrastructure within the project 'PuLS--Parken und Laden in der Stadt'.

### ORCID

Kalle Rauma  <https://orcid.org/0000-0002-5553-8751>

### REFERENCES

1. Anfinssen, M., Lagesen, V.A., Ryghaug, M.: Green and gendered? Cultural perspectives on the road towards electric vehicles in Norway. *Transport. Res. Transport Environ.* 71, 37–46 (2019)
2. Hardman, S.: Understanding the impact of reoccurring and non-financial incentives on plug-in electric vehicle adoption – a review. *Transp. Res. Part A Policy Pract.* 119, 1–14 (2019)
3. Napoli, G., et al.: Optimal allocation of electric vehicle charging stations in a highway network: Part 2. The Italian case study. *J. Energy Storage.* 26, 101015 (2019)
4. Funke, S.Á., Plötz, P., Wietschel, M.: Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany. *Appl. Energy.* 235, 888–899 (2019)
5. Kester, J., et al.: Policy mechanisms to accelerate electric vehicle adoption: a qualitative review from the Nordic region. *Renew. Sustain. Energy Rev.* 94, 719–731 (2018)
6. Gnann, T., et al.: Fast charging infrastructure for electric vehicles: today's situation and future needs. *Transport. Res. Transport Environ.* 62, 314–329 (2018)
7. Sovacool, B.K., et al.: Contested visions and sociotechnical expectations of electric mobility and vehicle-to-grid innovation in five Nordic countries. *Environ. Innov. Soc. Transitions.* 31, 170–183 (2019)
8. Hardman, S., et al.: A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transport. Res. Transport Environ.* 62, 508–523 (2018)

9. Levinson, R.S., West, T.H.: Impact of convenient away-from-home charging infrastructure. *Transport. Res. Transport Environ.* 65, 288–299 (2018)
10. KPMG.: Global Automotive Executive Survey. KPMG International. (2017) <https://home.kpmg/content/dam/kpmg/cl/pdf/2017-01-kpmg-chile-advisory-global-automotive-survey.pdf>
11. Blythe, P., et al.: Rapid Charge Network Activity 6 Study Report (2019)
12. Krause, J., Ladwig, S., Schwalm, M.: Statistical assessment of EV usage potential from user's perspective considering rapid-charging technology. *Transport. Res. Transport Environ.* 64, 150–157 (2018)
13. Jochem, P., Szimba, E., Reuter-Oppermann, M.: How many fast-charging stations do we need along European highways? *Transport. Res. Transport Environ.* 73, 120–129 (2019)
14. Botsford, C., Szczepanek, A.: Fast Charging vs. Slow Charging: Pros and cons for the New Age of Electric Vehicles. (2009)
15. Melliger, M.A., van Vliet, O.P.R., Lämätäinen, H.: Anxiety vs reality – sufficiency of battery electric vehicle range in Switzerland and Finland. *Transport. Res. Transport Environ.* 65, 101–115 (2018)
16. Norwegian EV policy, 2019. <https://elbil.no/english/norwegian-ev-policy/>.(2019) Accessed 28 Apr
17. Mahfouz, M.M., Iravani, M.R.: Grid-integration of battery-enabled DC fast charging station for electric vehicles. *IEEE Trans. Energy Convers.* 35(1), 1 (2019)
18. Gjelaj, M., et al.: Grid integration of DC fast-charging stations for EVs by using modular li-ion batteries. *IET Gener., Transm. Distrib.* 12(20), 4368–4376 (2018)
19. Hõimoja, H., Vasiladiotis, M., Rufer, A.: Power interfaces and storage selection for an ultrafast EV charging station. (2012)
20. Yunus, K., La Parra, H.Z.D., Reza, M.: Distribution grid impact of Plug-In Electric Vehicles charging at fast charging stations using stochastic charging model. In Proceedings of the 2011 14th European Conference on Power Electronics and Applications, 1–11 (2011)
21. Fathabadi, H.: Novel wind powered electric vehicle charging station with vehicle-to-grid (V2G) connection capability. *Energy Convers. Manag.* 136, 229–239 (2017)
22. Celli, G., et al.: Aggregated electric vehicles load profiles with fast charging stations,” in 2014 Power Systems Computation Conference. 1–7 (2014)
23. Simpson, M., Markel, T.: Plug-in electric vehicle fast charge station Operational Analysis with integrated renewables. In International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium 26 (EVS26). (2012)
24. Bryden, T.S., et al.: Electric vehicle fast charging station usage and power requirements. *Energy.* 152, 322–332 (2018)
25. Han, X., et al.: Economic evaluation of a PV combined energy storage charging station based on cost estimation of second-use batteries. *Energy.* 165, 326–339 (2018)
26. Ucer, E., et al.: Modeling and analysis of a fast charging station and evaluation of service quality for electric vehicles. *IEEE Trans. Transp. Electrif.* 5(1), 215–225 (2019)
27. Bryden, T.S., et al.: Rating a stationary energy storage system within a fast electric vehicle charging station considering user waiting times. *IEEE Trans. Transp. Electrif.* 5(4), 879–89 (2019)
28. Domínguez-Navarro, J.A., et al.: Design of an electric vehicle fast-charging station with integration of renewable energy and storage systems. *Int. J. Electr. Power Energy Syst.* 105, 46–58 (2019)
29. Mehrjerdi, H., Hemmati, R.: Electric vehicle charging station with multilevel charging infrastructure and hybrid solar-battery-diesel generation incorporating comfort of drivers. *J. Energy Storage.* 26, 100924 (2019)
30. Gjelaj, M., et al.: Multifunctional applications of batteries within fast-charging stations based on EV demand-prediction of the users' behaviour. *J. Eng.* 35(18), 4869–4873 (2019)
31. García-Triviño, P., et al.: Optimised operation of power sources of a PV/ battery/hydrogen-powered hybrid charging station for electric and fuel cell vehicles. *IET Renew. Power Gener.* 13(16), 3022–3032 (2019)
32. Yang, L., Ribberink, H.: Investigation of the potential to improve DC fast charging station economics by integrating photovoltaic power generation and/or local battery energy storage system. *Energy.* 167, 246–259 (2019)
33. Domínguez-Navarro, J.A., et al.: Design of an electric vehicle fast-charging station with integration of renewable energy and storage systems. *Int. J. Electr. Power Energy Syst.* 105, 46–58 (2019)
34. Tran, V.T., et al.: An efficient energy management approach for a solar-powered EV battery charging facility to support distribution grids. *IEEE Trans. Ind. Appl.* 55(6), 6517–6526 (2019)
35. Nicholas, M., Hall, D.: Lessons Learned on Early Electric Vehicle Fast-Charging Deployments, International Council on Clean Transportation, Washington, DC. (2018) [https://theicct.org/sites/default/files/publications/ZEV\\_fast\\_charging\\_white\\_paper\\_final.pdf](https://theicct.org/sites/default/files/publications/ZEV_fast_charging_white_paper_final.pdf)
36. Supponen, A., et al.: Power quality in distribution networks with electric vehicle charging - a research methodology based on field tests and real data. In 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), 1–11 (2016)
37. Rohde, L.: Electric Vehicle Fast Charging with Energy Storage and Generation Capabilities - Simulations Based on Real Charging Data. TU Dortmund University (2020) [https://eldorado.tu-dortmund.de/bitstream/2003/39007/1/Rohde\\_masterarbeit\\_final.pdf](https://eldorado.tu-dortmund.de/bitstream/2003/39007/1/Rohde_masterarbeit_final.pdf)
38. Ingeborgrud, L., Ryghaug, M.: The role of practical, cognitive and symbolic factors in the successful implementation of battery electric vehicles in Norway. *Transp. Res. Part A Policy Pract.* 130, 507–516 (2019)
39. Zhang, S.S., Xu, K., Jow, T.R.: The low temperature performance of Li-ion batteries. *J. Power Sources.* 115(1), 137–140 (2003)
40. Lorentzen, E., et al.: Charging infrastructure experiences in Norway - the worlds most advanced EV market. In EVS30 Symposium. (2017)
41. Korthauer, R.: Lithium-Ion Batteries: Basics and Applications. Springer (2018)
42. Tomaszewska, A., et al.: Lithium-ion battery fast charging: a review. *eTransportation.* 1, 100011 (2019)
43. Gandoman, F.H., et al.: Concept of reliability and safety assessment of lithium-ion batteries in electric vehicles: basics, progress, and challenges. *Appl. Energy.* 251, 113343 (2019)
44. Motoaki, Y., Yi, W., Salisbury, S.: Empirical analysis of electric vehicle fast charging under cold temperatures. *Energy Pol.* 122, 162–168 (2018)

**How to cite this article:** Rautiainen A, Rauma K, Rohde L, et al. Anatomy of electric vehicle fast charging: Peak shaving through a battery energy storage—A case study from Oslo. *IET Electr. Syst. Transp.* 2021;11:69–80. <https://doi.org/10.1049/els2.12005>