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The Market for Public Fast Charging of Heavy Trucks and How it Influences Prices, Capacity, and Queues.

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Executive Summary

The commercialization of heavy electric trucks is progressing, and many uncertainties about their effective use are resolved. For long-haul trucks, public charging will be used daily and could account for a large part of the total energy needs, making low charging prices at public chargers and no queues essential. This paper presents an early version of a model of the market for public charging and exemplifies how it can be used for examining factors like cost per kWh, charger capacity, charging queues, and the cost for building sufficient capacity to avoid queues. While price predictions are premature, the paper outlines key factors to keep charging costs and charging queues low.

Keywords: Electric vehicles, Heavy duty electric vehicles & buses, Charging business models, Fast and Megawatt charging infrastructure, Modelling and Simulation.

1 Introduction

In this paper some of the basic market mechanisms will be analysed using a model of aggregate demand, and it will be discussed some ways in which they influence the public charging system. The focus will be on how the specific cost per kWh is influenced by the charging demand, and what is required for the Charge Point Operators (CPOs) to build sufficient charger capacity to meet peaks in the demand, and thus also estimate when there is risk for queues. How the cost is then translated into price for charging at different times will also be discussed shortly, but exactly how that plays out is far more complex to model, as it depends strongly on how the users decide to react to price variations and queues.

The invisible hand is the metaphor used to describe how very basic behaviours of all the actors on a market normally will lead to an economically effective result on a system level, without anyone taking the whole system into account. The invisible hand seems to solve a lot of problems without a need for coordination or for anyone to understand exactly how. The attitude that the invisible hand will solve most problems is often justified in a fairly mature market, in which the market forces already have shaped the market into an effective form. However, the evolution caused by the invisible hand is not necessarily fast and accurate, and it can be very brutal against market actors. There is no guarantee that market forces find an effective path to build a new system, and therefore there is a risk for very costly investment mistakes if the early market actors do not have a good understanding of what the future public fast charging market may look like. Expensive lessons for major actors may lead to backlash and slow down the transition to electric vehicles. Consequently, it is very important to have a good understanding of the market forces for public charging of electric vehicles to allow a fast and effective transition. Such an analysis can also help authorities to find good policies to support the transition in ways that do not go against the market forces but work with them.

Note that the market forces are very complex. Therefore, we cannot expect to build a model which can predict all important results. Rather, we will have to simplify much to be able to find the core mechanisms, knowing that the models will miss some factors. This paper is an attempt to start building a very basic analysis in order to understand some important market conditions for public fast charging. It is intended to explain many important factors for actors who want to build or use public charging, but it will be too simple to make certain predictions.

This analysis is based on the assumption that public fast charging will mainly be controlled by market mechanisms and not by regulations, and that low entry barriers and many competing charge-point operators will lead to tough competition. When there is a need to be specific, the discussion and analysis will focus on examples from long-haul trucks, but the basic mechanisms will be similar for most types of public charging.

2 Market mechanisms

There are many possible ways in which to describe how the decisions, which shape the public charging infrastructure, are taken. It is often easy to imagine how it looks from the driver perspective and then it seems like the CPOs can set the prices rather freely while the charging stations' capacity and queues are out of your control. However, this way of looking at the system is misleading. What seems like free decisions by CPOs are not that free, but are tightly limited by economic market forces, which are largely driven by the drivers' decisions. Therefore, it is likely better to analyse pricing, queues and charger station capacity, not as decisions that someone can make, but rather as results of a market driven by demand and supply. This way of analysing the problem is not perfect, but it is likely to be able to describe the market mechanisms which set limits within which the drivers and the CPOs can operate. Notice that the drivers' preferences are captured in the description of their demand, which means that they will influence the outcome significantly. The CPOs are modelled as only being profit driven, but at the same time they are inexorably pressured by tough competition. I.e. it is mainly the drivers' behaviours which determine the outcome on the market. Therefore, it is mainly the system economy which is the "opponent" of the drivers, not the CPOs, and the drivers may feel like they have little power, when in fact they have most of the power, but only indirectly and only as a collective.

In Fig. 1 the market model used in this paper is shown. It can be seen that the CPOs and hauliers' influence on the market is only described as demand and supply, and then it is assumed that the market decides the price for charging, the capacity of a charging station, and if there will be queues or not. This model assumes that the market is mature with tough competition, such that there is little room for individual CPOs to dictate market conditions without being limited by their competitors. Note that this assumption may not be correct during phases of rapid growth in which competition may sometimes be weaker.

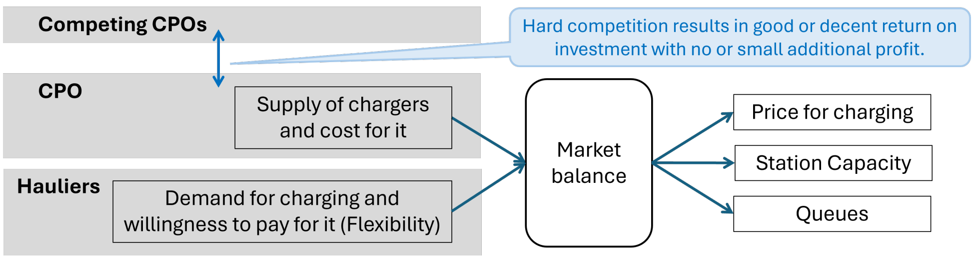

Figure 1: The simplified view of the public charging market used in this paper.

As a contrast, a detailed analysis of the charging market would require information about each vehicle, like its State of Charge (SoC), destination, its preferred arrival time, the drivers' breaks etc. Without those details, it cannot be predicted how a specific vehicle is likely to charge. Such an analysis will need to be made using, for example, agent-based modelling, tracking each individual vehicle and each charger. However, despite being more accurate, such a model results in an overwhelming amount of information, which is not easily understood and does not lend itself to reason and discuss about market forces in an effective way. This paper presents an aggregated demand model, aiming to include as few details as possible while still being useful for reasoning and discussing the likely outcomes on a market for public charging.

3 Aggregate local demand for public fast charging

The demand for public charging must be described in a way that allows it to be analysed together with the supply of chargers in such a way that the market balance can be found. That requires the demand to be described in terms of where and when vehicles want to charge, for how long they want to stay at the charger and how much energy they want to charge. If there are alternative options for how the vehicle can meet its charging demand there is also a need to describe the flexibility in demand, i.e. how much the haulier is prepared to pay for charging at the desired site before turning to alternative charging sites. All in all, there is a lot of information which can influence how and when a vehicle is charging. To capture all those details in a model which is easy to understand is hardly possible. In the traditional simplistic description of market theory, there is just one aggregate demand curve which describes how the demanded quantity varies with price. That demand is then meeting one aggregate supply. In that simple theory there is only **one** marketplace, where all transactions take place **simultaneously** between **all** sellers and buyers, and it is assumed that all offered products or services are equal. The market for public charging is far more complex. For example, the charging which takes place at one site is basically its own market and can have a different price than charging at the same site but another time and can also be different than the price for charging at another site at the same time. Thus, there isn't one single market price decision, but one price decision at each time and each site. To make it even more complex the demand for charging a specific vehicle cannot only be met at one site and one time, but there is flexibility, which means that the prices on one site will be influenced by the prices on nearby charging sites, as some vehicles can decide to use one or the other. Similarly, there is sometimes a flexibility in when a vehicle starts its trip, leading to even more flexibility in the demand.

3.1 Charging demand at one site

To focus on the main mechanisms, the model assumes that the number of charging vehicles and the number of charge points are continuous variables and not integers as in the real world. This may seem like introducing errors, and in one sense it does, but it also provides an advantage in the analysis as the steps created by only being able to build integer number of chargers will often be so big that they make it difficult to spot the underlying trends. Since this model is intended to analyse market mechanisms rather than the exact market outcome, it is an advantage that the model does not need to deal with the step effects in a real system. Stations with fairly many charge points seem to be a little more cost-effective than smaller stations, so they are likely to be common. For these bigger stations, integer steps will have less impact, and the approximation will thus be quite realistic for them.

In this section, it is described how the aggregate demand at one geographical site can be described as the number of vehicles that want to charge simultaneously, and the total charger power required, including their time variation. For one site, the demand can be derived from how frequently vehicles arrive to charge at that site, expressed in vehicles per hour. That determines the rate at which chargers are being occupied by new vehicles. Then the time they need to stay and charge is used to determine when they depart from the charging station. Each vehicle has its own desired charging time, but for the whole charging station it does not matter much which vehicle wants to stay long or short. For a station with many chargers, it is sufficient to know the average charging time. The frequency of arriving vehicles per hour is called $n_{Arr}(t)$ and their average charging time T_{ChgAv} which in this paper is assumed to be 30 min, since the resting time rules for truck drivers are requiring different types of breaks to be at least 15, 30 or 45 minutes. Assuming that there is a sufficient number of chargers to meet the demand, the vehicles will on average leave the chargers T_{ChgAv} later than they arrived, such that the frequency of departing vehicles becomes

$$n_{Dep}(t + T_{ChgAv}) = n_{Arr}(t) \quad and \quad n_{Dep}(t) = 0 \ \text{ for } \ t < T_{ChgAv} \tag{1}$$

The number of vehicles which want to simultaneously charge at the station is, in this method, used as the definition of demand. Starting from an empty charging station, the demand becomes

$$N_{ChgDmd}(t) = \int_0^t (n_{Arr}(t') - n_{Dep}(t')) \cdot dt' \quad . \tag{2}$$

At a constant frequency of arriving vehicles, $n_{Arr-SteadyState}$, for a longer time than T_{ChgAv}, the number of vehicles that charge simultaneously at the station will be proportional to the frequency that new vehicles arrive with a constant of proportionality T_{ChgAv} i.e.

$$N_{ChgDmd-SteadyState} = T_{ChgAv} \cdot n_{Arr-SteadyState}. \tag{3}$$

An example of the charging demand is shown in Fig.2. The blue curve shows the frequency of vehicles arriving to charge. During the night, 6 vehicle/h arrive, then 18 vehicle/h from 9:00 to 20:00, except for a peak of 30 vehicle/h from 17:00 to 18:00. With an average charging time of 30 min the departing vehicles follow the red dashed curve. Using Eq.2 and starting from $N_{ChgDmd-SteadyState}$ the number of charging vehicles will then follow the black curve. Notice that the unit for the frequency of arriving and departing vehicles is vehicle/h, while the charging vehicles is just a number of simultaneously charging vehicles. Even with stepwise changes in the frequency of arriving vehicles, the number of charging vehicles does not change in steps but rather has a ramp increase which is determined by the average charging time.

For the CPO it is the number of simultaneously charging vehicles that determines how many charge points are required, and it does not matter if the number of vehicles depends on a high frequency of arriving vehicles or if

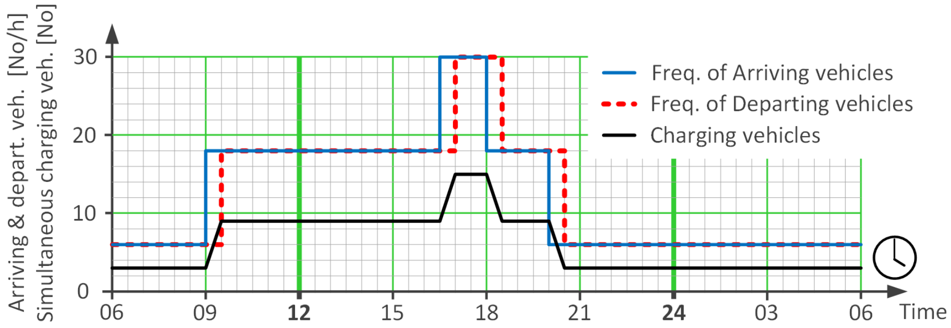

Figure 2: Arriving and departing vehicles and the number of simultaneously charging vehicles.

the vehicles charge for a long time. To describe the demand in a compact way, it is defined by the black curve showing the number of simultaneously charging vehicles, as that curve captures both the effect of varying inflow and varying charging time.

Long-haul truck drivers will have to follow the rules for driving and resting time, and that means that their charging behaviour most likely will be more even than for car drivers. The rules mandate either one 45-minute break, after no more than 4.5 hours of driving. Alternatively, the 45-min break can be divided into one break of no less than 15 minutes, no earlier than 2.5 hours after the driver started to drive, and then an additional 30-minute break after at most 4.5 hours driving. That means that it will be highly likely that trucks stop either 15 min, 30 min or 45 min. To stop less than that is unlikely, since the break does then not fulfil the rules. Stopping significantly longer than required reduces the productivity of the driver and truck, so that is also rather unlikely. Because of this, long-haul trucks may have low requirements for really high charging power and minimized charging time and instead are likely to prefer the lowest cost for charging the required energy during the fixed time of the driver break.

3.2 Demand for charger power

It is also important to describe the demand for charger power since it influences the cost for the chargers. This section only discusses the required aggregate total charging power for all charging at one site. The total power demand can be estimated in many ways, depending on what type of information one has available. Generally, it will be estimated from knowing which type of vehicles charge at different times, and how much energy they on average need to charge, and whether they want to charge as quickly as possible or if they have a fixed time they want to stay at the charging station. As this paper is not about how to derive the demand, but rather how to use the demand to analyse market forces, the power demand is in this paper just estimated from the average charging power per vehicle, $P_{ChgAv}(t)$, multiplied by the number of charging vehicles

$$P_{ChgDmd}(t) = N_{ChgDmd}(t) \cdot P_{ChgAv}(t) \tag{4}$$

In this paper average charging power will not be varied with time, but the method allows for that. Note that we have so far not discussed anything about how much the vehicles are prepared to pay for charging, and how the demand changes with price. This is intentional, to keep the complexity in the analysis low. Instead, the analysis in this paper will assume an inelastic demand, meaning the same volume is requested irrespective of price. The market analysis will then be made and the cost for charging will be an outcome of the analysis. Afterwards the cost can be compared with estimates of the willingness to pay for charging, to determine if it is likely that the demand is decreased or increased. If so, a modified demand can be introduced, and the market can be analysed again.

4 Supply of charging capacity

4.1 Required charging station capacity to meet the demand

The supply of charging capacity is modelled as fully elastic. As the public charging market is expected to have low entry barriers for new CPOs, and all competing CPOs can buy the required charging equipment and construction work at basically the same price, it is assumed that the cost for the charging station is similar for all competing stations, irrespective of the capacity of chargers built. The fully inelastic demand and fully elastic supply make it easy to determine the outcome on the simplified market. The main question will be to determine the cost for a station that meets the demand. At a later stage, the consequences of not building sufficient capacity will be analysed, to see if it can be expected that it is profitable for the CPOs to build sufficient capacity to avoid queues.

The total net capacity of a station P_{StnCap} is describing how much charging power it can practically deliver at the same time on all its charge points together. A second measure of the station capacity is the number of vehicles that can charge simultaneously N_{StnCap}. The demand for charging can be met if

$$P_{StnCap} \geq P_{ChgDmd} \quad \text{and} \quad N_{StnCap} \geq N_{ChgDmd} \tag{5}$$

These requirements must be fulfilled independently, but as long as the average power of the charging vehicles is known, the capacity in terms of number of vehicles is proportional to the capacity in terms of power.

$$N_{StnCap} = \frac{P_{StnCap}}{P_{ChgAv}} \tag{6}$$

Many components in the charging station will need to be over-sized relative to the station's capacity N_{StnCap}, and P_{StnCap}. One reason is that the actual power delivered by the individual charge points varies significantly during, and between, charging sessions. Therefore, the charge points must be sized for a much higher peak power than the average power they deliver when charging a vehicle. A second reason is that the charge points will not be used all the time, as it takes some time to change charging vehicles when a vehicle is leaving the station. However, the over-sizing factors are only needed when determining the cost per kW for building a station with a certain capacity. They are not visible in the below analysis of the sizing of the station as a whole.

4.2 Cost for a charging station

The total cost for a charging station will include capital costs, monthly fees for grid and costs for operating the station, as well as costs for the electric energy drawn from the grid. A way to make it easier to understand what influences the cost and how, is to split the cost into one part that the CPO has for providing and operating the charging station, and another part which depends on how much energy is charged. This way of splitting the cost may be used when negotiating contracts between CPOs and hauliers. Some contracts may only focus on agreeing the price for **using** the chargers, while they might not include the cost for the energy, which then instead will vary according to its price during the actual charging session. With such pricing the CPO takes much less risk if they make long-term agreements on the price with their customers, since the risk caused by unpredictable variations in electricity prices is not placed on the CPO, but on the haulier. In fact, there is an advantage of the hauliers bearing the cost for varying energy prices, as they are the ones who can adapt their charging to the varying price for electricity; something the CPO cannot.

Despite having many different costs for building and operating a charging station, it turns out that the total cost is roughly proportional to the station power capacity

$$C_{StnYr}(P_{StnCap}) = c_{StnYr} \cdot P_{StnCap} \tag{7}$$

The total cost for providing chargers, c_{StnYr}, includes the capital cost for the station with its grid connection, a required return on the invested capital, annual cost for using the grid, and operating costs for the station. There are also some small fixed costs, like for planning of the station and base costs for a charger management system, but they are generally so small compared to the other costs that they do not need to be included in order to understand the basic market mechanisms influencing the sizing of charging stations. In this paper $c_{StnYr} = 117$ EUR/kW/yr from [1] is used, and the same cost will per day be $c_{StnDay} = 0.32$ EUR/kW/day. Note that these costs do not include the cost for the energy and energy-based tax and fees. The prices for the electric energy in Sweden are set by trading on a power exchange (Nordpool). It differs between different parts of Sweden and varies by the hour. However, since the effect of varying electricity prices is not the scope of this paper, an estimated fixed price of 0.1 EUR/kWh will be assumed, which includes the average price on Nordpool, the Swedish energy tax and grid transmission fees.

4.3 Cost per kWh and Energy utilization

The total cost for the station is calculated by Eq.7, but it is not the total cost for the station which determines if it is cost-effective, but rather the cost divided by the amount of energy charged by all the station's users. The more energy is charged, relative to the station capacity, the lower the cost per kWh will be. Therefore, we define the energy utilization factor to describe how efficiently the station capacity is used. The definition of the energy utilization for a general case over a time period T, and specifically over a time period of one year, are

$$k_{EnUtilT} = \frac{W_{ChgT}}{P_{StnCap} \cdot T} \qquad \text{and specifically} \quad k_{EnUtilYr} = \frac{W_{ChgYr}}{P_{StnCap} \cdot 1\ \text{Yr}} \tag{8}$$

where W_{ChgT} is the total energy charged at the station during a time period T, and W_{ChgYr} is the total energy charged during a whole year. Energy utilization is here defined for the whole station, but it is also a relevant measure for an individual charge point, or groups of charge points. The energy utilization will be 100% if the station delivers its full power constantly for the full time period T and will be zero if no one charges at the station. A well-designed station will, during the short time periods with peak demand, be close to 100% energy utilization, but for determining what charging price is required to make the station profitable, the utilization over a full year is the relevant measure, since the costs are specified per year. The annual average cost per charged kWh can, using Eq.8, be calculated as

$$c_{chg} = \frac{C_{StnYr}}{W_{ChgYr}} = \frac{c_{StnYr} \cdot P_{StnCap}}{W_{ChgYr}} = \frac{c_{StnYr}}{\text{1 Yr}} \cdot \frac{1}{k_{EnUtilYr}} = \frac{\text{0.013 EUR/kWh}}{k_{EnUtilYr}} \tag{9}$$

This cost function is plotted in Fig 3. Notice that the charging cost does not depend on the station's power capacity, except indirectly through its influence on the energy utilization. Also, the cost of c_{StnYr} =117 EUR/kW/yr was translated in Eq.9 to a cost of 0.013 EUR/kWh by dividing it by one year (8760 h). Thus, since the energy utilization cannot be higher than 100%, the lowest possible cost for the charging station is 0.013 EUR/kWh, and that is when the station delivers charging at its peak capacity day and night, all year. Of course, 100% energy utilization is not at all realistic, but if the energy utilization is 10%, the cost is 0.13 EUR/kWh, and at 1% utilization the cost for charging will be 1.3 EUR/kWh. There are, of course, other dependencies, hidden by the simplifications in the modelling, but these will be second-order effects, and when analysing the basic market forces they can normally be left out, until a more detailed analysis of a specific station is needed. For example, the size of the station has some influence on cost per kWh; low number of charge points in a station likely increases c_{chg} a little.

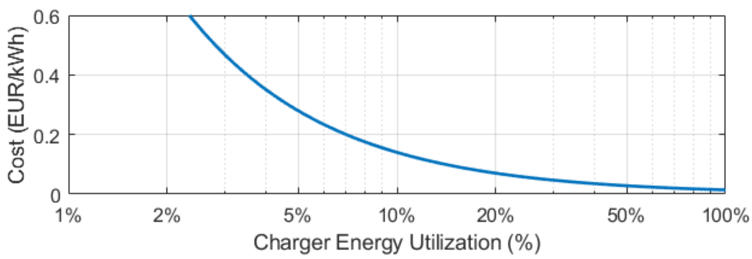

Figure 3: Fixed cost for a charging stations per delivered kWh as a function of energy utilization.

What makes this way of analysing the cost so attractive is that the utilization can easily be found from the shape of the demand curve and the capacity of the charging station. To make it easy to illustrate we analyse energy utilization based on one day, rather than a full year, but the method is the same for a full year. If the station capacity is higher than the peak demand and the demand is not influenced by the cost of charging, i.e. is inelastic, the actual charging at the station will be equal to the demand. The energy charged at the station, during the analysed day, can be expressed as the time integral of the charging power and is proportional to the area under the demand curve. The energy utilization can be determined as

$$k_{EnUtilDay} = \frac{W_{ChgDay}}{P_{StnCap} \cdot T_{day}} = \frac{\int_0^{\text{24 h}} P_{Dmd}(t) \cdot dt}{P_{StnCap} \cdot \text{24 h}} \tag{10}$$

Visually this is the same as comparing the average height of the demand curve with the capacity of the station, so it is easy to "see" the energy utilization from just a glance at the demand curve and the station capacity. Notice that this is the utilization for just one typical day, but we need the utilization for a full year to determine the cost per kWh. To make this conversion easy we just assume that we know how well the energy charged during the analysed day corresponds to the average charging power over a whole year. If the day we analyse is a typical weekday we can assume that the average daily utilization over a whole year is, say, 70% of the utilization for the analysed day. The yearly utilization is lower due to seasonal variations in demand and a lot of days during a year with lower demand than in Fig.2, like during weekends. So, let's assume

$$k_{EnUtilYr} = \frac{W_{ChgDay} \cdot 70\%}{P_{StnCap} \cdot \text{24 h}} \tag{11}$$

which can be used to determine the utilization, which together with Eq.9 can be used to determine the cost per kWh. The power demand is plotted in Fig. and it has the same shape as the demand in Fig.2 which showed the demand expressed as the number of simultaneously charging vehicles. The shape is the same as we assume a fixed average charging power per truck of P_{ChgAv} = 500 kW. First, we assume that the station has a power capacity of 10 MW, represented by the purple line A in Fig.4. The energy demand over the whole day, represented by the grey area, is 72 MWh resulting in an average power demand of 3 MW, illustrated as the dashed black line. The utilization and cost per kWh of charged energy for a station capacity of 10 MW then is

$$k_{EnUtilYrA} = \frac{72\text{ MWh} \cdot 70\%}{10\text{ MW} \cdot 24\text{ h}} = 21\% \qquad c_{chg} = \frac{0.013\text{ EUR/kWh}}{21\%} = 0.062\text{ EUR/kWh} \tag{12}$$

Lowering the capacity of the station will increase its energy utilization and reduce the cost per kWh. If the station power capacity is lowered to 7.5 MW, shown as the purple line B in Fig.4 the energy utilization and cost per kWh instead becomes

$$k_{EnUtilYrB} = \frac{72\text{ MWh} \cdot 70\%}{7.5\text{ MW} \cdot 24\text{ h}} = 28\% \qquad c_{chg} = \frac{0.013\text{ EUR/kWh}}{28\%} = 0.046\text{ EUR/kWh} \tag{13}$$

So, generally there is a cost advantage to reduce the station capacity as that reduces the cost per kWh, but as can be seen in Fig.4 a station capacity of 7.5 MW is the lowest capacity that is possible if the demand shall be met. In a later section we will study what happens when the capacity is too low, as in cases C and D.

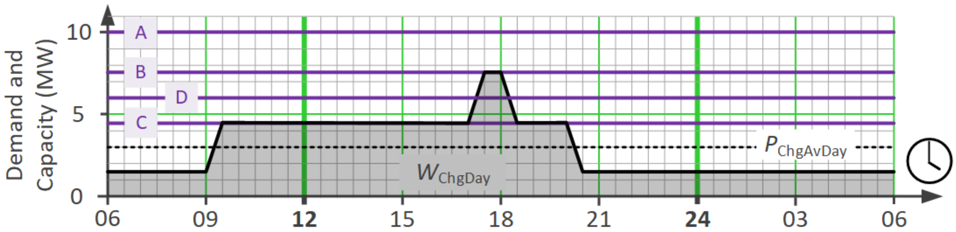

Figure 4: The power demand for a site (black curve), and some examples of station power capacities (purple lines).

Based on Eq.8 we can draw conclusions about what shape the demand curve should have to allow for a high energy utilization. In Fig.5 four different simplified demand curves are shown. To reduce cost per kWh the station capacity shall be low while the delivered energy shall be high. If the demand shall be met the station's capacity has to be as high as the peak in the demand. Notice that it does not matter if the station is big or small, it is just the ratio between the peak in the demand and the energy demand which shall be high. Therefore, demand curve **a** in Fig.5 is the best possible choice, as it maximizes the surface under the curve (=energy charged) for a given height (=required capacity). This demand corresponds to an even flow of trucks to the charging station all hours of the day, and it can result in an energy utilization of 100%. As the other extreme we find demand curve **d**, in which no vehicles want to charge for almost the whole day, except for a short time in the afternoon. This station requires the same capacity as demand **a** but delivers only a fraction of the energy. Its energy utilization is therefore close to zero. Demand **b** and **c** both require the same station capacity as they have the same height of the demand peak, and they deliver a similar amount of energy, resulting in the same energy utilization of about 50%. The fact that they look very different but result in the same energy utilization illustrates that a lot of details in the demand curve are not very important, as long as we know the peak demand and the total energy demand. From a cost perspective demand curves **b** and **c** are thus equivalent. However, they may be different when it comes to how the price is set over the day and also how attractive it is for the CPO to build sufficient capacity to avoid queues, as is discussed later.

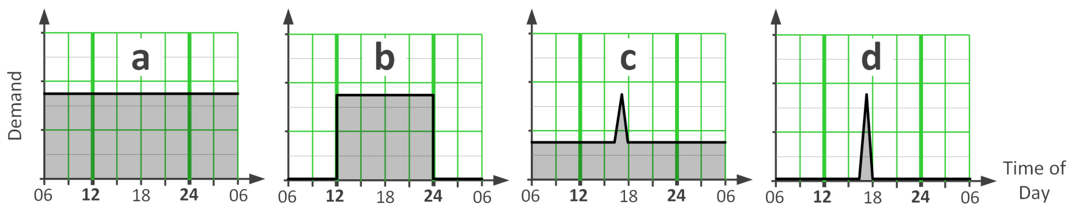

Figure 5: Examples of some very different demand curves, all having the same peak demand.

In this section we have seen how we can determine the station capacity required to meet the demand, and how to determine the cost per kWh. However, we do not yet know if the market forces will push the CPOs to build sufficient capacity to always meet the demand. Therefore, that will be studied in the next section.

5 Charging queues

5.1 Station capacity and queues

A major concern for anyone planning on using public charging for electric vehicles is if there will be queues at charging stations, and if so when, and how long one will need to queue before being able to start charging. In Fig. 6 the demand from Fig.2 is shown again, together with two different station capacities which are lower than the peak demand. In the lower diagram the station's capacity is 12 simultaneously charging vehicles and in the upper diagram it is 9 vehicles.

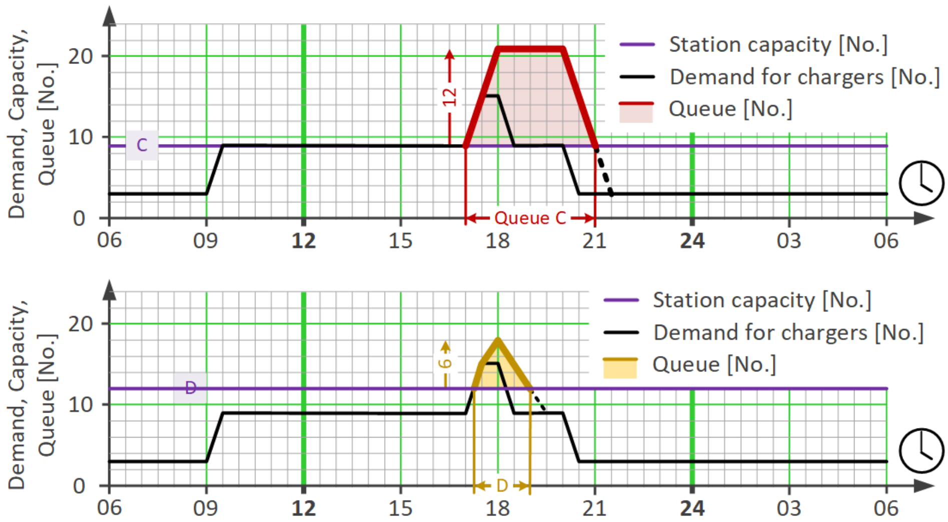

Figure 6: Charging demand and queue as function of time for two different station capacities.

In the upper diagram, it can be seen that a capacity of 9 simultaneously charging vehicles, case C, is too low to meet the peak demand of 15 simultaneously charging vehicles. When the demand exceeds the capacity, a queue will start to form. Exactly how to calculate the queue will not be derived in this article. However, it is rather easy to understand what will happen. In case C all chargers were already taken before the peak started at 17:00, so the number of charging vehicles cannot increase, despite more vehicles arriving. Therefore, the excess in arriving vehicles starts to form a queue, growing like the red curve in Fig. 6. It does not stop growing at 17:30, which the demand did, since the departing vehicles will not increase above the level it had before 17:00. Instead, it stops growing first at 18:00 when the frequency of arriving vehicles drops from the peak of 30 vehicle/h to the level the station has capacity for, 18 arriving vehicle/h. The queue is 12 vehicles long when it stops growing, but the queueing problem is far from over. Now the queue must be worked off, but since the capacity of the station is fully used by the arriving vehicles, the queue length remains the same until 20:00, when the demand drops below the station capacity. First then, the queue can be worked off. When the red line crosses the capacity of the station at 21:00, the queue is eliminated, and thereafter the number of occupied chargers follows the dashed black line until it reaches the demand curve and starts following it again. We notice that there has been a queue from 17:00 to 21:00, and for a long time, 12 vehicles queued. The total aggregate queueing can be measured as the number of queue-hours, and that is the red coloured area, which in this case will be $T_{\text{QueueTotC}} = 36$ vehicle hours. Notice that we talk about the total queueing time for all vehicles using the station during these hours. The vehicles who made up the queue when it formed after 17:00 will not need to stay until after 20:00, as the queue is continuously being emptied at one end and filled with new vehicles at the other end. The time an individual vehicle will need to stand in the queue depends on the queue length before that vehicle entered the queue, $N_{Queue}(t)$, the station capacity N_{StnCap}, and the average charging time

$$T_{Queue}(t) = \frac{N_{Queue}(t)}{N_{StnCap}/T_{ChgAv}}. \tag{14}$$

In the above example, 12 vehicles are queueing when a new vehicle arrives. Since the station capacity is 9 charge points, and the average charging time 30 minutes, the arriving vehicle will need to queue for 40 minutes. This is a bad queueing situation, and it illustrates how quickly queueing can become an issue, if the capacity is not high enough. Contributing to the long queueing time is that fact that there was no spare capacity to work off the queue directly after the peak in demand, at 18:00.

If the demand is not flexible, as in the present example, the only way to reduce the queue is to increase the station capacity. If the capacity is increased to line D in the diagram, the situation becomes better. First of all, the queue does not start growing until 17:15. Secondly, the growth rate of the queue is lower as the capacity is only exceeded half as much as in case C, resulting in a queue which at most has 6 vehicles. Also, as soon as the frequency of arriving vehicles drops at 18:00, there is some spare capacity and the queue starts to reduce and is eliminated at 19:00. The total queueing time is $T_{\text{QueueTotD}} = 5.6$ vehicle-hours. That is much lower than in case C, since fewer vehicles stand in queue and the queue is present for a shorter time. The vehicle which stands the longest time in queue waits for 15 minutes according to Eq.14. This is much better than case C, but a period of one hour and 45 minutes with queues can still not be seen as a good situation.

So, why is the queueing such a pronounced problem? The main reason lies in the fact that once the capacity is exceeded, the queue grows continuously until the peak ends. So even though a one-hour peak in demand may seem short, quite a long queue can be accumulated, and then there is also a need for additional time to work it off.

To derive the queue length and total queueing time is a little more complicated than just taking a glance at the demand curve and comparing it with the station capacity, since it requires integrating the difference between arriving vehicles and departing vehicles. However, the demand curve still provides a quick way to estimate the queueing conditions. For example, the queue will start to grow as soon as the demand exceeds the capacity. The bigger the difference between demand and capacity the faster it will grow. Notice that we have assumed that all vehicles which want to charge will stay and wait in a queue, which of course is not likely. Therefore, the demand curve is mainly useful to determine the capacity limit at which queues can occur; it will also be useful to estimate a worst-case scenario for the queue. However, to predict how long queues there will be also requires analysis of the driver behaviour when facing a queue.

5.2 Cost for avoiding queues

In the previous section, it was clear that too low station capacity will lead to queues, and now we will analyse how much it costs to avoid those queues. Avoiding the queues at minimum cost requires the station capacity to be increased to just be as high as the peak demand, i.e. 15 charging spots, and 7.5 MW of station power capacity. According to Eq.13 that leads to a cost of 0.046 EUR/kWh for the chargers in addition to the 0.1 EUR/kWh for the energy cost. (This is a very low charging cost, but that is because the demand in this example is a very favourable one.) If instead the capacity is 6 MW, case D, the energy utilization and cost per kWh is

$$k_{EnUtilYrD} = \frac{72 \text{ MWh} \cdot 70\%}{6 \text{ MW} \cdot 24 \text{ h}} = 35\% \qquad c_{chgD} = \frac{0.013 \text{ EUR/kWh}}{35\%} = 0.037 \text{ EUR/kWh} \tag{15}$$

and at a capacity of 4.5 MW, case C, the energy utilization and cost per kWh is

$$k_{EnUtilYrC} = \frac{72 \text{ MWh} \cdot 70\%}{4.5 \text{ MW} \cdot 24 \text{ h}} = 46.7\% \qquad c_{chgC} = \frac{0.013 \text{ EUR/kWh}}{46.7\%} = 0.028 \text{ EUR/kWh} \tag{16}$$

Thus, comparing these results to Eq.13 it seems like the bad queues in case C can be eliminated for only a cost increase of (0.046-0.028) EUR/kWh = 0.018 EUR/kWh and the lighter queues in case D cost (0.046-0.037) EUR/kWh = 0.009 EUR/kWh to avoid. That seems like a low cost, but before we draw conclusions the cost should be compared to how much queueing it avoids. To do that requires the total cost for avoiding the queues, rather than the cost per total kWh. The extra cost per day for extending the capacity from C to B is

$$\Delta C_{\text{Day C to B}} = W_{ChgDay} \cdot (c_{chgB} - c_{chgC}) = 72 \text{ MWh} \cdot 0.018 \text{ EUR/kWh} = 1296 \text{ EUR/Day} \tag{17}$$

and dividing by the total queueing time we get the cost per hour of avoided queueing

$$C_{\text{AvoidQueueC}} = \frac{\Delta C_{\text{Day C to B}}}{T_{\text{QueueTotC}}} = \frac{1296 \text{ EUR}}{36 \text{ h}} = 36 \text{ EUR/h} \tag{18}$$

This is about the same as only the salary cost for the driver during the queueing, and since there is also cost for the truck when it is not productive it is good business to pay 36 EUR/h to avoid queueing with a heavy commercial truck. The same calculations for avoiding the queues in case D result in a cost of 648 EUR/day but with only 5.6 vehicle-hours of queue in case D, the queue-avoidance cost is 116 EUR/h. That is more than the total cost for a waiting truck and driver. So, it is not clear that it is cost effective to increase the capacity from 6 MW to 7.5 MW to avoid the queues in case D.

5.3 Who will pay for the required capacity?

For queues to be avoided in a free market it is not sufficient that the cost to do it is low, it must be profitable for the CPO to build the capacity required to eliminate the queues. The previous analysis calculated the increased cost per kWh for all the energy charged at the station, and that was found to be low, so it is, from a system perspective, not very expensive to avoid the queues in this example. But will the competition allow the CPOs to get extra income from all its users to pay for capacity that is only used during the rush hours? The answer to this question depends on how the customers will change their charging when a station builds more or less capacity.

One way to allocate the cost for the additional peak is to assume that the extra capacity for the peak is paid for by increasing the price during the peak. How much higher the price must be per kWh during the peak can be calculated by dividing the cost for increasing the station capacity by the total energy that will be charged at a higher price. In the upper diagram in Fig.7 the peak in the demand and energy during the peak are shown, when the station capacity is increased by ΔP_{StnCap}=3 MW, from 4.5 MW to 7.5 MW. The green area W_1 is the increased charging which can be provided during the peak by the increased capacity. However, if the price is higher during the peak the higher price will be paid for all charging during that period, i.e. $W_1 + W_2$. So, we can determine a price increase during the peak which would be sufficient to pay for increasing the capacity to avoid the queues

$$\Delta c_{\text{Peak}} = \frac{\Delta P_{\text{StnCap}} \cdot c_{StnDay}}{W_1 + W_2} = \frac{3\text{ MW} \cdot 0.32\text{ EUR/kW/day}}{3\text{ MWh/Day} + 6.75\text{ MWh/Day}} = 0.098\text{ EUR/kWh} \tag{19}$$

This cost will make it significantly more expensive to charge during the peak hours. Also, the narrower the peak the less energy the cost is divided by, making it even more expensive to charge during narrower peaks. Should the peak be much higher the price increase will also be higher. Even worse, a peak which only occurs once per month, will cost about 30 times more per kWh as 30 days of charger cost shall be divided by energy that is charged only once per month. So, it seems this pricing method will lead to very high prices for rare peaks or very narrow peaks.

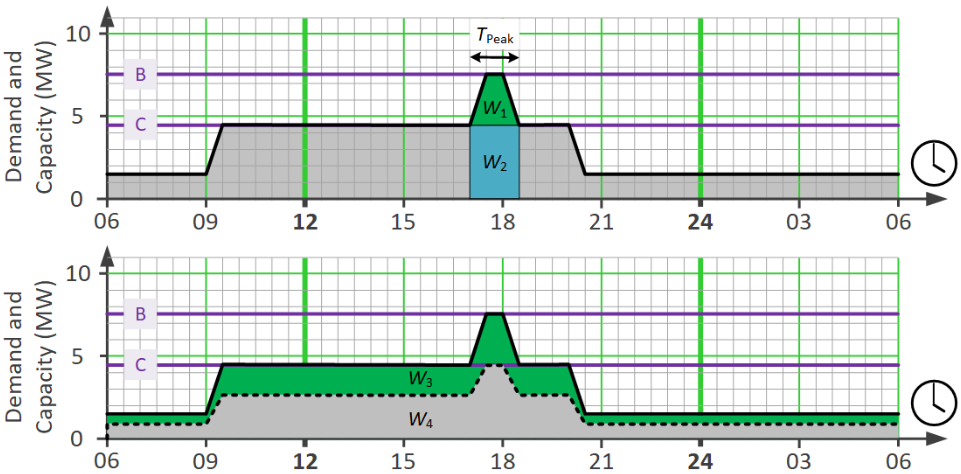

Figure 7: The charging which pays for the capacity required for a peak in demand. Upper diagram when demand is not influenced by the station capacity, and lower diagram when demand is proportional to the station capacity.

However, this may be an overly pessimistic way of calculating. The above calculation would be correct in a monopoly situation. If there are no competing charging stations, the utilization of the charging station outside the queueing period will not be influenced by any extra capacity built to avoid queues. So, under monopoly, the additional charger will only increase the income during the short time of the peak. However, if an additional charger capacity will attract more customers, not only in the peak but also off-peak, then the situation is very different. Assume that there are two stations at the same site, and they both have the same prices over the day, due to tough competition. It is not known exactly how the off-peak demand is influenced by additional capacity, but it seems reasonable to expect that an increased station capacity of, say, 10% would attract 10% more customers at all times. That is the same as assuming that the stations share the customers at the same ratio as the ratio of their station capacity. That will result in an increase in charging that is equal to the green area W_3 in the lower diagram in Fig. 7. It is likely that customers will avoid a station where they have experienced queues, even outside rush hours. Humans often follow habits and may then make a general decision of which station they prefer, and then stick to that station most of the time. Such a behaviour will be favourable for building capacity to avoid queues, as the additional chargers built will have similar energy utilization as the existing chargers, and that will generally make it profitable to build them, at least until the demand during the peak is met by all the stations at the studied site. On the other hand, this may be a too optimistic assumption, but it shows a possible mechanism that may make it likely that the CPOs will profit from building capacity to avoid queues. It also demonstrates that the collective behaviour of the customers is important for how much queueing problem there will be, if any.

6 Discussion about the market for public charging

6.1 How will the cost per kWh translate into price for charging?

So far, it has been discussed what cost a CPO has for providing a charging station and how the demand influences the cost per kWh, but it is important to stress that the analysis has not yet answered the question of what the price will be for charging. The key to understanding how prices can be set is to understand how different pricing models influence how the customers select charging station, and when they will charge. This question is not easily analysed with an aggregate model like the one in this paper. Rather, an agent-based model [1,2] is a good tool for such investigations, or other models which can capture the charging decisions of different users and express that as their willingness to pay for different levels of demand. Despite this shortcoming, we are not clueless about the prices. With the assumption that competition will not allow for high profits beyond a reasonable return on investment, the average price for charging must be the same or a little higher than the cost per kWh. It is only the price variation over days, weeks, and years that is not yet answered in this paper. So, the presented model gives a good understanding of what makes a charging station cost-effective, but most likely there will be time-varying charging prices which cannot be predicted with this method, at least not yet.

6.2 Flexible demand and willingness to pay for the charging

The analysis in this paper was made assuming inflexible demand, and since it is likely that some users will change their charging plans depending on queue-conditions and due to possible time-varying prices, we can conclude that results based on inflexible demand may be a little pessimistic. If some users avoid charging in rush hours, there is a possibility for the peaks being flattened and widened, which is favourable as it reduces the required capacity to meet the total energy demand and thus reduces the cost per kWh.

In a short term perspective, the flexibility may be limited, as most vehicles have limited possibilities to change the charging plan once they have planned their trips, without some negative effects. However, in the longer perspective the flexibility will generally be higher. Learning the general pattern of when and where there is a risk for queues may make vehicle users change when and how they plan their trips, and that may result in a more significant type of flexibility. For example, if there is a lot of spare capacity during nights and early morning, and that allows a haulier to negotiate much lower charging prices at those times, some hauliers may find ways to reschedule some of their trips to those times and thus reduce the demand during daytime.

6.3 Discussion about charging queues.

On a system level, the cost for avoiding queues will depend on how high the peaks in demand are, relative to the total energy demand. So, exploring how the demand varies with time will be a key to predicting how likely queues are. If the peaks are not so much higher than the average demand, the cost to avoid queues will not be very high. But even then, some queues may occur. One reason is that peaks at levels that only occur seldom will be expensive to build capacity for. So, if there are rare occasions which have significantly higher demand than normal days, they may result in queues, while queues are not so likely during normal days since the cost to avoid them will be more reasonable, as the capacity built to avoid them is used most days.

Even if it is profitable to build capacity to avoid queues, they may occur since it takes a rather long time to build more capacity. Unexpected increases in charging demand may, therefore, lead to temporary queues. Especially, such problems may occur during an expansion phase for electric vehicles, in which the demand for charging may grow at a fast rate, which may be difficult to predict.

On the positive side, there may be other reasons to build extra capacity than only to avoid queues. For example, it is expensive to need to very urgently repair any broken charger. Thus, it may be cheaper to build a little extra capacity than to require that service personnel must be available on short notice any time. That may result in a typical station having higher capacity than what would otherwise be economically motivated, maybe about 5-10% higher. Also, if queueing is a factor which strongly discourages a user from future use of a charging station, that will increase the economic incentives to build sufficient capacity to avoid queues.

7 Conclusions

This paper has presented a way to analyse basic market forces for public chargers based on aggregated charging demand as a function of time. The method can help understand the basic market mechanisms which influence the cost for charging, how many chargers are likely to be built, and when there is a risk for queues. This model can, however, not yet explain how the price for charging is likely to vary, as that requires a more detailed understanding of the behaviour of different customers.

Some highlights:

- This paper introduces a way to describe the charging demand as one function showing how many vehicles want to charge simultaneously at different times, and another function describing the total charging power demand at different times. The demand will be different for different places.
- The energy utilization of a charging station will be the main factor deciding cost per kWh, and it can be determined from only the demand curve and the station capacity.
- The demand curve can also be used to determine when there can be queues and estimate the worst-case queues at a charging station. Combined with a cost model the additional cost per kWh for avoiding different queues can be determined.
- How the prices will vary over the day, week and year will largely depend on how the customers reacts to price signals and queues.

Future research: This model development is only at an early stage and the aggregate model and its use can be developed further to answer many more questions, like for example the cost for charging stations aimed for different types of vehicles, and the synergies when several vehicle types can share charging stations. The questions about the risk for queues and the incentives to build sufficient capacity to avoid queues need a thorough analysis to draw clearer conclusions.

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Presenter Biography

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His research is system-oriented and focuses on how to coordinate vehicles, infrastructure, and vehicle operations to create cost-effective, robust, and flexible systems. He collaborates with vehicle OEMs, fleet operators, charger operators, authorities, and energy utilities. The results of his research are used to guide and facilitate the large-scale electrification of mainly heavy trucks and city buses.