THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

System Cost Evaluation and Fast Charging Market Assessment for Battery Electric Trucks

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Abstract

One possible step for reducing human use of fossil fuel due to transportation is to replace diesel trucks with battery electric ones. This thesis considers the potential for battery electric trucks to be cost effective in the long run. It investigates how to size the batteries and chargers for different transport tasks and compares the cost effectiveness of electric trucks with commercial diesel trucks. The thesis focuses its examples on long-haul trucks, but a large part of the developed theory can be applied to other trucks and vehicles as well. Further, queueing conditions, charger utilisation and price levels in a future public fast charging market are estimated. This is done by agent-based models, simulating competing charge point operators and charging trucks with traffic data from a Swedish highway. The aim of the work is to gain better understanding of a possible future system of battery electric trucks and their chargers, and what is important to make them cost effective. Also, it aims to find an estimated value for the mean price for public fast charging, which is important for the trucks charging strategy and could affect the overall cost effectiveness of the electric trucks. The results indicate that battery electric trucks can be competitive compared to commercial diesel trucks in many cases, and the utilisation of the public fast chargers can be quite high with low queuing problems and reasonable charging prices. Hopefully, this positive result will accelerate the transition from trucks running on fossil fuel to trucks running on electricity that can be sustainably produced.

Keywords: Battery electric truck, cost effective, battery sizing, charging strategy, utilisation, public fast charger, charge point operator, competition, driving pattern, agent-based model.

Included Publications

This thesis intends to summarise the work done in the following papers:

A Karlsson, J; Grauers, A. "Energy Distribution Diagram used for Cost-Effective Battery Sizing of Electric Trucks". *Energies*, **2023**, *Volume 16, Issue 2*, 779.

B Karlsson, J; Grauers, A. "Case Study of Cost-Effective Electrification of Long-Distance Line-Haul Trucks". *Energies*, **2023**, *Volume 16, Issue 6*, 2793.

C Karlsson, J; Grauers, A. "Agent-based Investigation of Charger Queues and Utilization of Public Chargers for Electric Long haul Trucks". *Energies*, **2023**, *Volume 16, Issue 12*, 4704.

D Karlsson, J; Grauers, A. "Agent-Based Investigation of Competing Charge Point Operators for Battery Electric Trucks". *Energies*, **2024**, *Volume 17, Issue 12*, 2901.

E Karlsson, J; Grauers, A. "Competition Between Geographically Spread Charge Point Operators for Battery Electric Trucks—Estimations of Prices and Queues with an Agent-Based Model". *Energies*, **2025**, *Volume 18, Issue 10*, 2453.

Paper A, Paper B and Paper C have earlier been included in the authors licentiate thesis [1] while Paper D and Paper E was not.

Work in the Papers Not Done by the Author of This Thesis

The contributions by the different authors are shown under "Author Contributions" at the end of each paper. However, below the things *not* done by the author of this thesis for each paper are listed:

A
- The invention of the energy distribution diagrams.
- The extraction of the costs that differs between a battery electric truck and a diesel truck.
- The text in chapter 2 "Designing Electromobility Systems Using Energy Distribution Diagrams".
- Selecting the "typical values" shown in Table 1 and the value of the number of operation days for a truck.

B
- Designing the fictive haulage company with help from contacts in the industry.
- Finding the values in the table in the left-hand side of Figure 2.
- Finding the parameter values in Chapter 4, "Cost of Losing Payload Capacity".
- Appendix A, B, C and D.

C
- Finding the values for the speed and energy consumption of the trucks.
- Selecting the source for the data used.
- The assumption that a 900 kW charger on avarage delivers 700 kW.

D
- Creation of Figure 3.

E
- –

Remarks

The following errors have been detected in the papers:

A –

B –

C
- The last term in equations 2 and 3 should be divided by the useful battery capacity. This is missing in the paper.
- The numerator in the left-hand side of equality in equation 6 should be 0.0134 EUR/kWh instead of 0.134.

D
- Figure 2 in Paper D is incorrectly plotted. The last value of the data is missing in the figure. This has also resulted in that each value in the plot is a little bit too wide to fill the space for the missing value. A better way of illustrating the data is given in Figure 4.12.

E –

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DEK

Contents

1 Introduction

Humanity's widespread use of fossil fuel has severe drawbacks. The oil could be depleted in some decades [2], the earth climate system has likely been affected [3] and concerns of poor air quality and health impacts are expressed in the literature [4]. Based on data from the Swedish government authority "Naturvårdsverket" [5] and the European Parliament [6] one may calculate, see Appendix, that heavy duty trucks are responsible for about 6% of Sweden's total greenhouse gas emissions during year 2023 and approximately 5% in the European Union during year 2019. Thus, a part of the solution to the problems mentioned could be to replace commercial diesel trucks with so-called zero emission trucks. Among the zero emission trucks, battery electric ones seem promising since several studies have shown that they could be cost competitive to diesel trucks during right circumstances [7][8][9][10][11]. Also, the feasibility for battery electric trucks seems promising [12].

Even though the battery electric truck seems to be a good replacement for diesel trucks other powertrains are also considered in the literature. Hydrogen trucks could be a part of the solution [13], but battery electric trucks seem to be the better option in general [14][15]. However, hydrogen trucks might be more suitable for heavy duty trucks on extra-long trips [16]. A literature review [17] states that battery electric trucks have advantages compared to diesel trucks, such as lower emissions, lower maintenance costs and higher energy efficiency but also disadvantages such as limited range and higher vehicle cost. The limited range for battery electric trucks is of course a drawback, and the term "range anxiety" was coined some decades ago refers to electric vehicle users' fear of getting stranded with an empty battery [18]. To achieve a longer range the use of heavy trucks running on liquefied biogas has been suggested, but they do not seem to be cost competitive with conventional diesel trucks without political subsidies [19]. Yet another study suggests biofuel for long-haul trucks since they, at least then (year 2015), were considered difficult to electrify [20]. If one compares battery electric trucks with biodiesel, the electric trucks will result in less air pollution, even if one charges the trucks with a mix of electricity like the one used in the United States of America during 2017 which consisted of 10% coal among others [21]. Naturally, the environmental impact of battery electric trucks depends on the electricity used to charge them. For example, a study [22] highlights that the emissions of greenhouse gases from the electricity in many cases are clearly larger than the emissions from the production of the batteries. In closing the discussion of different powertrains, there is no powertrain that is the most cost effective in all cases since it depends on how the vehicles are used [23].

So, what are prerequisites for cost efficient battery electric trucks? An early study emphasized a sufficiently low battery price for mass production of electric vehicles [24]. Other essential factors for cost effective battery electric trucks are for example the battery size [25] and the number of cycles the batteries can perform [26]. Even the choice of cell chemistry can affect the cost-effectiveness which is discussed in the literature [27]. The transport task, or in this thesis, synonymous with the truck's driving pattern is also important. For example, a study [28], finds that heavy duty pre and post haulage of containers are favourable for electrification due to short/medium trips and sufficient available charging time during loading and unloading. According to the study, they were cost competitive to the diesel trucks already at year 2023. How the transport task, or the driving pattern affects the cost effectiveness of the battery electric trucks is one of the main questions that are investigated in this thesis and how one should size the battery for different driving patterns. In addition, the cost competitiveness for a realistic transport task is explored. This is performed by analytic calculations. When this was done many assumptions had to be made, some of them could benefit the cost effectiveness of the battery electric trucks but the main principle has been to not favour them. For example, in this thesis the battery price is set to 200 €/kWh but the literature [29] claims that it will reach below 150 €/kWh at year 2035 at latest. Another principle has been to mainly include the most important parameters for clarity and therefore excluded details that might affect the result to some extent but likely do not matter for the bigger picture. Like the possibility for battery electric trucks to use energy grid storage to get extra income (charge at low price hours in the depot and sell back to the grid when the electricity price is higher). To disregard this can be justified by that an early study finds that energy grid storage with car batteries has low profitability potential [30], and it means that the resulting cost effectiveness is estimated conservatively.

Although fast charging can have negative effects on battery health [31], fast charging for long-haul trucks is expected to be needed [32] and will be available with the new MCS-standard (Megawatt Charging System-standard). The MCS-standard will be able to deliver maximum 3.75 MW and is even suggested to be oversized for truck applications [33]. The future public fast charging market for trucks is expected to have low entry barriers [34] and many different actors can possibly be charge point operators, such as logistics service providers, fuel stations, energy companies, and truck manufacturers [35]. Thus, hard competition is expected which hopefully leads to reasonable prices. This thesis considers battery electric trucks with stationary charging, but there exist other technical solutions. Dynamic charging, using so called electric road system, could strongly reduce battery size [36]. There is also a possibility for time savings with the technique "battery swapping" which could be performed in 3-15 minutes, as compared to 30-60 minutes for fast charging [37]. The charging of battery electric trucks will require much power from the local grid [38] and within a few years, up to 5000 public fast chargers for trucks may be needed in the European Union together with Great Britain, Norway and Switzerland [39]. As a reference, there will likely be need for several times more slow chargers [40]. The price for fast charging is vital for long-haul trucks to be cost competitive compared to diesel trucks [41]. Fixed prices dominate the early market for public fast charging in Europe (year 2025), however, prices that vary with time geography have been discussed in the literature [42]. From Paper A and Paper B included in this thesis it is clear that the price on the future public fast-charging market is indeed very important to study, which is done in Paper C, Paper D, and Paper E. In these papers it is assumed that there is competition and a possibility for the seller to have different prices at different times of the day, and the investigations are done using agent-based models. Agent-based models simulate the actions of autonomous individuals (the agents), see for example, [43] for an introduction. Agent-based models are a well-established simulation method and have been used, for example, to study competition in biology [44], disease spreading [45], segregation in society [46] or electric roads systems for battery electric vehicles [47]. Reference [48] considers agent-based models as a "key tool for planning and decision making" for electrified transportation. The author of this thesis considers agent-based models as powerful tools since they can give system insights and macroscopic results only by designing rules for the actors on a microscopic level.

The title of this thesis is "System Cost Evaluation and Fast Charging Market Assessment for Battery Electric Trucks". The word *system* refers to the system of battery electric trucks and their chargers. The result from this thesis shows that battery electric trucks could be a cost-effective alternative to today's commercial diesel trucks, and it also shows that the basic market mechanisms can make it possible to have a future well-functioning public fast-charging market with reasonable prices, low queueing problems, and profitable charge point operators.

2 Similar Studies, Research Gaps and Contributions

In this section it is explained how this thesis complements and contributes to the existing research field of battery electric vehicles and in particular battery electric trucks and their chargers. Similar studies to the ones included in this thesis will be presented along with the differences and research gaps.

With support of Reference [24] an influential study [49] focusing on personal cars states, "It is commonly understood that the cost of battery packs needs to fall to below US$150 per kWh in order for BEVs to become cost-competitive on par with internal combustion vehicles" where the abbreviation BEV stands for Battery Electric Vehicle. In Paper A it is shown that battery electric trucks can be cost-competitive with commercial diesel trucks already at a battery price of 200 €/kWh which is approximately equal to 200 US $/kWh at the time of writing. One important difference in this context between personal cars and commercial trucks is the driving patterns, which often are more suitable for commercial trucks than for private cars and can thereby explain the positive result from Paper A. In Paper A the so called "Energy distribution diagram" (EDD) is introduced as a useful tool for evaluating the economics of different driving patterns and sizing the battery for them. The EDD summarises the driving pattern for a vehicle's whole service life in a compact way and will be explained later in this thesis. The fact that battery electric vehicles are sensitive to driving pattern is emphasized by an early study [50], using probability density functions for the daily distance travelled by electric cars. In the eyes of the author the EDD is a slightly improved tool compared to the probability density function for the daily distance travelled when dealing with electric vehicles. This is because it does not involve any randomness and shows the energy consumption which is better than the distance travelled since the same distance can give rise to different energy consumptions due to different weather conditions or payload.

There are many trade-offs to consider when one wants to find efficient system solutions for battery electric trucks. For example, small or medium batteries lower the battery cost significantly compared to a large battery but can result in time loss for en route charging [51]. Reference [52] conclude that larger batteries and higher power of the chargers can significantly reduce extra charging time for battery electric truck. However, to higher purchase prices. Paper A treats the trade-off between a large and expensive battery with medium-power depot charger versus a smaller battery with low-power depot charger and more public fast charging. The authors have not found another study exploring this for battery electric trucks. It appears that the EDD is useful in selecting the right battery capacity for this trade-off. In [50] two cases are investigated, one case when the household has an extra internal combustion car to use when the daily distance cannot be managed by the electric car and another case when an expensive rental car must be used when the distance cannot be covered by the electric car. They find that the sensitivity to the driving pattern is larger in the case when one must use the rental car. This has similarities with Paper A if one considers the extra car to be similar to fast charging. In Paper A the fast charging is quite expensive compared to depot charging and one result is that the total cost of battery electric trucks is sensitive to driving patterns. Likely this sensitivity decreases if the price for public fast charging needed, for trips that cannot be covered by only depot charging, is lower. Reference [7] has similarities with Paper A, but one difference is that they put a fix price on charging and thus do not take in to account how to select battery size in order to change the ratio of the amount of energy charged in the depot to the amount of energy charged with public fast chargers. Their focus is also not as much on the fact that different driving patterns give different cost effectiveness. Paper A is also more general in the sense that it analyses more driving patterns, such as a truck with two different but *arbitrary* transport tasks while [7] investigates a truck with two specific transport tasks. This also characterises Paper A, it is more general than many of the referred studies in this thesis. The goal of the paper was to understand the main mechanisms that affect the cost effectiveness of the battery electric truck. To make this clearer the comparison with diesel trucks has been done as simple as possible (but not simpler). In contrast to [53] which makes a very detailed comparison which includes for example insurance, maintenance and driver costs which are simply assumed to be equal for the diesel and electric truck in Paper A. The author of this thesis thinks that simplification can increase understanding and that all small differences from each simplification hopefully will cancel out decently, or in some cases it can be accepted that one knows that the answer is not fully correct as long as you know the sign of the error. There exist studies that focus on feasibility such as [54]. They conclude that the feasibility for a heavy-duty battery electric trucks fleet is good for drayage trucks (transportation of shipping containers). This thesis does not focus on feasibility. It is assumed that all realistic trips are feasible with the right battery size and charger power. While this might be true one may ask, is these trips cost effective to electrify or how can we make them cost effective? The theory developed in Paper A is helpful when considering these types of questions.

At the start of the investigations resulting in Paper B (year 2022) the electrification of trucks was not yet far gone. Worldwide there existed less than 60 thousand battery electric trucks according to [55] which can be compared to 6 million trucks only in the European Union in 2025 [56]. In the beginning of the 2020s the literature [57] considers heavy duty long-haul trucks as difficult to electrify and reach cost parity to diesel trucks. It was also a common opinion in the industry, at least in Sweden, that this type of transport would be clearly expensive with battery electric trucks [58]. One study [59] was found that was optimistic about the cost competitiveness for long-haul battery electric trucks already in year 2018, however, they did not include the cost for the charger and grid connection which they say, "would amount to a significant increase in upfront costs" and justifies this due to "uncertainty around subsidies". So, their result could be seen as overoptimistic. The mentioned study [57] declares "This study highlights the need for additional research by considering real-world use cases and explore how additional powertrains compare to conventional vehicles in the near future. Variations in daily driving distance may be unavoidable for many use cases. Fast charging EVs or PHEVs could be explored as the solution to address range uncertainties." where EV and PHEV stand for electric vehicles and plug in hybrid electric vehicles. Paper B fills this important research gap and industrial concern by making a case study where a made-up company wants to electrify their trucks. The design of the transport task is inspired by the Swedish haulage company "Tommy Nordbergh åkeri AB" and the transport task is typical for Swedish line-haul trucks. Paper B uses the theory developed in Paper A and finds that the battery electric trucks are cost competitive to commercial diesel trucks under the price picture presented in the paper. This price picture is meant to be realistic when battery electric trucks are produced in high volumes.

In Paper B the price for public fast charging was partly explored. From the paper it was clear that the price could have strong effect on the optimal charging strategy and battery size. A later study [60] confirms that the cost-effective battery size is sensitive to the price for public fast charging and that it is important to have an idea of the price level when selecting and manufacturing batteries. Also, there was a big concern among the haulage-companies in Sweden that there might be severe queues at charging stations with high prices on public fast charging and charging booking system was frequently discussed [58]. Paper C, Paper D and Paper E aim to investigate if this will be the case using agent-based models. In all these papers the intended charging need from the Swedish highway "Europaväg 4" (E4) at full electrification of the truck fleet is used. Paper C finds that there seems to be possible to achieve high charger utilisation and at the same time low queueing problems at fast charging stations. The use of booking system is questioned, and it seems that one may expect reasonable prices for fast charging due to high charger utilisation, without much queuing. It is found that the drivers' unwillingness to queue is an important property to improve the queuing condition in the system, this result is confirmed by a later study [61]. In Paper C it was also found that few stations with many chargers resist queues better than many stations with fewer chargers when the total number of chargers was equal. A similar result had earlier been presented in Reference [62].

In Paper D two competing charge point operators at the same site are explored. The paper shows that it seems likely that time varying prices will outcompete fixed ones. It also shows that competition will likely lead to a system with low queueing problems and low or reasonable prices for public fast charging. To the authors knowledge, this is the first study that uses an agent-based model to simulate competition in a future public fast charging market for trucks. Since this market is not yet in a mature state Paper D contributes to understanding the possible conditions in this future market.

Roughly speaking Paper E is a study of the combination of the mechanisms in Paper C and Paper D. In this paper the competition between charge point operators along highway E4 is simulated. This time there are several sites along the road, each with two charging stations. All charging stations are in competition with each other. To formulate charging problems as pure optimisation problems has been done in the literature [63], in that case to minimise the number of chargers for electric buses. In Paper E the setup of optimal number of chargers and prices over the day is dependent on the competitors set up (which can change). Therefore, the author thinks it is hard to treat the problem as a pure optimisation problem. Once again, the agent-based model becomes a natural choice since it "just" tries to mimic reality rather than explicitly optimizing. Paper E aims to find a market equilibrium after sufficiently long time of competition. The simulations were performed with two different types of truck behaviour, one when the truck drivers were sensitive to prices and one when they were sensitive to queues at charging stations. It was found that the haulage companies, as a collective, have large power over the future fast charging market. If they want to charge to low prices, they will get low prices to the cost of more queues in the system and if they do not want to queue there will be low queueing problems in the system, but they will charge to a higher, but still reasonable, price. It is also shown that the EU Alternative Fuel Infrastructure Regulation (AFIR) [64] could have some negative effects when forcing charging stations at every 60th km along the Trans-European Transport Network (TEN-T) core road network. Even another study [65], applying the agent-based model "MATSim" for battery electric trucks in Sweden, claims that one should not follow the AFIR strictly. They show that the charging need not always follows the placement of charging stations forced by AFIR. They claim that following AFIR strictly could result in charger stations with poor utilisation. In Paper E the utilisation of future public fast chargers along the E4 highway is estimated to 18%. This value is by the author considered quite good since it includes strong resistance towards queues. High utilisation of future fast chargers is also predicted by [66], which finds an even higher utilisation (30% - 53%) with MATSim along large roads in a future case in Sweden. There could be many reasons for that the utilisation found in [66] is clearly higher than the one found in Paper E. However, to the author there seems to be at least three important differences. Firstly, there are different types of data used, the data used in [66] is not available but likely it has a more even traffic flow. Secondly, in [66] the successful electrification ratio of the trucks is 90% instead of 100% as in Paper E, if this should be increased to 100% it should require more chargers which likely should decrease the utilisation. Thirdly, in [66] they make simulations on a "typical day" just as in Paper E, however in Paper E the utilisation is later compensated for expected flow variations over the year which lower the utilisation, this is not done in [66]. Even with these three aspects in mind, one cannot deny that the utilisation reached in [66] is high which supports the quite high utilisation found in Paper E. The author in a contemporary study [34] describes its own paper as an early attempt to create an analytic approach for the charging queues, utilisation of the chargers and price for public fast charging for battery electric trucks. This method is significantly different from the agent-based models. With the analytic approach one has more control, but one can hardly manage as complex situations as with the agent-based models. If this analytic method could be developed and applied, it could work as a plausibility check when performing simulations in simplified cases with agent-based models. Such plausibility check is done in Paper D but not in Paper E.

3 Battery Electric Trucks, Charging Infrastructure and Simplifications

This thesis investigates the potential for a future cost-effective system of battery electric trucks and chargers. Notice that the work focuses on the future case where the whole truck fleet is electrified. This means that the values of the cost parameters presented later in this thesis only is valid when there are large production volumes of battery electric trucks and chargers. Also, the charging needs for the trucks used in this thesis are meant to be realistic when the transition from diesel trucks to battery electric ones is made.

It is assumed that the truck have access to a private charger at the depot and that there is a possibility to use public fast chargers along the roads. The public fast chargers will typically be of much higher power than the depot chargers so they can charge a considerable amount of energy during driver breaks, while the depot charger could be used for several hours when the truck is standing inactive in the depot.

In this thesis many simplifications has been made, and they will be presented and motivated later in this thesis, but some examples are:

- The power a charger delivers is independent of the trucks state of charge.
- The local grid owner will always provide the needed grid capacity at a charging station as long as the charge point operator pays for it.
- All truck drivers behave in the same way in the same simulation.

The author's goal has been to make reasonable simplifications to avoid having minor details obscure understanding of the fundamental cost- and market-mechanisms that shape the future system of trucks and chargers. Hopefully, none of the simplifications have led to significant errors. The three simplifications above can respectively be motivated according to:

- If the truck charges a large part of the useful capacity the charging time is approximately the same if the average power is used instead of the instantaneous charging power. Also, the charge point operators has in the later articles paid for higher power of the charger and grid connection than for the average power, to compensate for the increased charger size required to handle the variation in charging power.
- It is reasonable to believe that, sooner or later, the needed grid capacity will be installed if the charge point operator pays for it.
- Even though all drivers will not behave in the exact same way this method makes it possible to estimate upper and lower bounds for example the charging prices. Such as if all the truck drivers are clearly price sensitive this will likely result in a price which will be around the lowest possible price in a future public fast charging market. Also, it is easier to understand the core mechanisms that shape the system from analysing pure cases rather than realistic cases with a lot of variation in behaviours.

4 Summary of the Papers

The aim of this research has been to develop better understanding of system solutions for battery electric trucks and their chargers and investigate price levels and potential queueing problems in a possible future public fast charging market if all trucks are battery electric. This market is not yet mature; therefore, the outcomes will likely be of interest and importance for both haulage companies and CPOs (charge point operators) for their electrification strategies. This section aims to summarise the included papers so that the main findings and the basic knowledge can be learned with less effort than reading all the separate articles. Hopefully this summary will facilitate the understanding of the totality and explain why this content is important. However, to be able to fully understand and question this content it is recommended to read the attached articles as well. The articles are more stringent and aim to explain everything in such a way that the investigations can be repeated by the reader.

This chapter is structured as follows: first the influential costs for a battery electric truck are identified, then it is shown how they can be minimised, after that the developed theory is applied to a fictitious haulage company with a realistic transport task. From the results one notices that the cost for public fast charging is of great importance when selecting charging strategy and it also impacts the overall cost effectiveness of the battery electric trucks. As the possible minimum price for charging strongly depends on the charger utilisation, the utilisation of truck chargers along a Swedish highway is investigated under the condition that the queueing problems should be small. This was done via an agent-based model where the trucks were treated as agents, and they try to charge at the lowest price and at the same time avoid large queues. The results look promising but since the number of chargers was tuned manually and the prices just was set without profit interest from the CPOs the interest to extending (and hopefully improving) the model was raised. Therefore, a new agent-based model was constructed where competition was added. Now, the CPOs, as well as the trucks, are treated as agents. The trucks aim to minimise a total cost for charging which includes queueing cost while the CPOs try to adjust their prices and number of chargers to increase their profit. This model investigates two competing CPOs at the same site. So, as a final step one may roughly say that the two models were combined into one. An agent-based model, with trucks driving along a highway and charging to be able to complete their transport task. Avoiding large queues and high charging prices while several CPOs along the road adjust their number of chargers and prices over the day to increase the profit. A quasi-equilibrium is reached where, for example queues and charging prices could be studied, which hopefully represents the future conditions in a mature public fast charging market.

4.1 Cost of a Battery Electric Truck

To be able to find cost effective solutions for battery electric trucks a cost function, f_{BEV}, is formulated. The cost function only considers the main cost that differs compared to the diesel power train. For example, cost for maintenance and insurance are omitted. The electric truck excluding the battery is assumed to have the same purchase price as the diesel truck. Under the assumption that charging of the trucks is carried out during already planned breaks, even the salary of the driver can be left out. This is a reasonable assumption since regulation (EC) No 561/2006 [67] stipulates that drivers must take a break after no more than 4.5 h of driving. However, the haulage companies can decide battery capacity and charging power for the depot charger, when buying the truck and its charger. Even though the charging strategy can be decided by the haulier, the possibilities depend on the battery capacity, available charging power and the transport task for the truck. when calculating the cost, the charging strategy can be described by the ratio of the amount of energy charged at private depot chargers to the total amount of energy charged during the vehicles service life. The energy that is not charged at the depot charger comes from public fast charging which is assumed to be more expensive than depot charging. Let the cost for the electricity be C_e when charging in the depot, the cost for public fast charging C_{epub}, the battery cost C_b, the cost for the charger $C_{charger}$ and the cost for the grid connection C_g. Further, the length of the service life for the vehicle, battery and charger is T. The value of the cost function will be normalised and expressed in Euro per *propulsion* kWh. As a reference, the price for the fuel cost for a diesel powertrain C_d is used. This cost is based on a diesel price of 1.2 €/l (excluding VAT) and a high powertrain efficiency of 40%. The values used in this thesis are shown in Table 4.1. Later in this thesis it will be shown that the price for public fast charging may, in many cases, be lower than the assumed value in Table 4.1.

Table 4.1: Notations for the different cost parameters and their assumed values.

Costs	Notation	Typical Value
Diesel Cost	C_d	0.30 €/kWh
Electricity Cost, Private Charging	C_e	0.08 €/kWh
Electricity Cost, Public Fast Charging	C_{epub}	0.4 €/kWh
Battery Cost	C_b	200 €/kWh
Price of Charger	$C_{charger}$	400 €/kW
Grid Fee	C_g	60 €/kW/year
Service Life of Truck, Charger and Battery	T	7 years

Now the cost function for the battery electric truck can be formulated as

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b \cdot B_c}{E_{tot}} + \frac{C_{charger} \cdot P_{ch}}{E_{tot}} + T \cdot \frac{C_g \cdot P_{ch}}{E_{tot}}, \tag{4.1}$$

where the new introduced parameters are defined in Table 4.2.

Table 4.2: Notations for truck and usage parameters.

Parameters	Notation
Total Propulsion Energy Consumed Over the Trucks Service Life	E_{tot}
Ratio of Private Charging to the Total Amount of Energy	r_{ch}
Battery Capacity	B_c
Charger Power	P_{ch}

The first term in the above equation is the cost for depot charging, the second term is the cost for public fast charging, the third term is the battery cost followed by the cost for the charger and finally the cost for the grid connection. By naming the total amount of energy from the depot charger over the trucks service life E_{ch} and since $r_{ch} = \frac{E_{ch}}{E_{tot}} \iff E_{tot} = \frac{E_{ch}}{r_{ch}}$ the cost function can be written as

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\frac{E_{tot}}{B_c}} + \frac{r_{ch}}{\frac{E_{ch}}{T \cdot P_{ch}}} \cdot \left(\frac{C_{charger}}{T} + C_g \right). \tag{4.2}$$

To be able to rewrite the above equation a battery utilisation and a charger utilisation will now be defined. Firstly, the battery utilisation, Γ_b, is defined by the amount of energy that is delivered by the battery over its service life divided by the battery capacity, i.e.

$$\Gamma_b = \frac{E_{tot}}{B_c}. \tag{4.3}$$

The battery utilisation has therefore the dimensionless unit *equivalent full cycles* (EFC) and describes the number of *full* discharge cycles that corresponds to the total energy the battery delivers during its life. Secondly, the charger utilisation, Γ_{ch}, is defined by the amount of energy that is converted by the charger over its service life divided by the *maximum* possible amount of energy that could be delivered by the charger over its service life, i.e.

$$\Gamma_{ch} = \frac{E_{ch}}{T \cdot P_{ch}}. \tag{4.4}$$

Thus, the charger utilisation is a dimensionless scalar in the interval $[0, 1]$ often expressed in percent. By introducing the combined cost parameter for the depot charger and corresponding grid connection $C_{ch} = \frac{C_{charger}}{T} + C_g = 117$ €/kW/year, the cost function can be expressed as

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\Gamma_b} + \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}. \tag{4.5}$$

As seen from the above expression it is preferable to achieve high values of the battery and charger utilisations since that decreases the cost for every kWh delivered by the battery, charger and grid connection. At the same time, one wants r_{ch} to be high since a small value increases the cost for public fast charging. Small batteries and chargers result in high utilization but could demand a higher share of public fast charging. If one can find a relationship between these three influenceable parameters one is able to use one-dimensional calculus to find the minimum value of the cost function. In the next subsection the *energy distribution diagram* (EDD) will be introduced as a way of describing the trucks transport task. It will be shown that the shape of the EDD connects the three influenceable parameters and thus make it possible to minimise the cost function for an electric truck.

4.2 Energy Distribution Diagrams

The energy that a battery electric truck consumes each day will differ due to, for example, different transport tasks, varying load and weather conditions. The data for the daily energy consumption for a truck can be presented in an energy distribution diagram. At first, consider a trucks daily energy consumption over one week in the left-hand part of Figure 4.1, where the height of each bar on the y-axis represent the energy consumed for that day. Over a truck's service life the number of days are many and if they are sorted with respect to energy consumption, starting at the highest consumption, one obtain a curve which is called the energy distribution diagram [1], see the right-hand part of Figure 4.1. Let the total number of days during the vehicles service life be N_{tot} and the number of days the vehicle is operating be N_{op}. It is not a problem that the days are rearranged according to energy consumption if it is assumed that the truck is fully charged during the night. Then the energy available for one day is independent of the consumption the day before. Sorting the days according to energy consumption has advantages as it is easier to read out, for example, the highest daily energy consumption or to estimate the mean energy consumption. Also, it is easier to approximate the sorted EDD with a mathematical function that is always monotonically decreasing. Notice that it is possible to change to number of trips instead of number of days on the x-axis, for a vehicle which is charged after each trip.

By plotting the useful battery capacity in the EDD it is also possible to determine how many days the battery is too small to run the whole day on one charge. These days the vehicle needs to fast charge during the day. In this thesis it is assumed that fast charging only charges the minimum energy needed to carry out the rest of the days driving. Thus, the energy which needs to be fast charged can be determined as the red-striped area in the diagram and the energy charged from the depot charger corresponds to the blue striped area, see Figure 4.1.

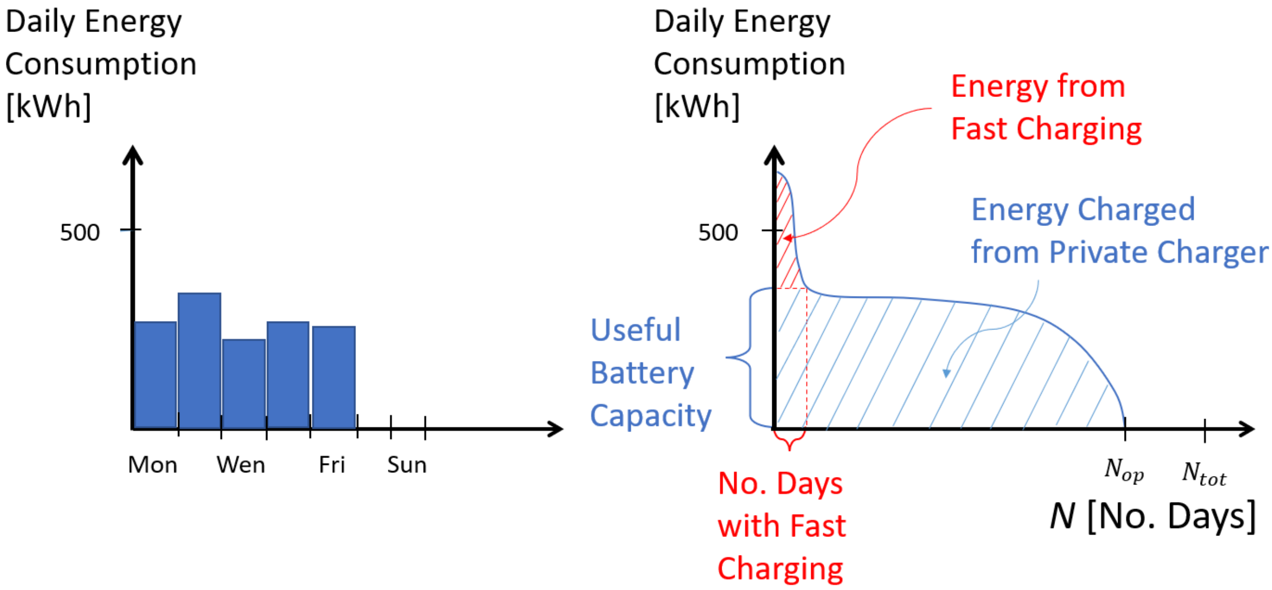

Figure 4.1: The daily consumed energy for five working days to the left and the energy distribution diagram for a truck's full service life to the right. In the right-hand part of the figure the number of days that need fast charging and the amount of fast charging needed is marked with red for a certain useful battery capacity.

The EDD gives a lot of information for the full service life of a vehicle in a compact way. This information is listed below:

- The total energy consumption is the area under the curve.
- The total number of operation days is where the curve meets the x-axis.

---

[1] Notice that curve actually should be a discrete number of points but for convenience it is instead seen as continuous curve.

- The mean consumed energy for the days when the truck is used equals the total energy divided by the number of operation days.
- The highest consumed energy in one day is where the curve meets the y-axis.
- The number of days requiring fast charging and the amount of fast charging needed for a particular useful battery capacity.
- The shape of the EDD provides an easy way to see how large the variation in daily energy consumption is and how large share of the days that have high, medium or low energy consumption.
- Maybe most important, the EDD connects the useful battery capacity with the parameter r_{ch}, since r_{ch} can be found as the blue striped area divided by the area under the curve (see Figure 4.1).

When considering the right-hand part of Figure 4.1 one may suspect that the optimal charging strategy is strongly influenced by the shape of the EDD. For example, can it be a good idea to select a battery capacity that can handle most of the trips but not the thin peak in the EDD? In that case the battery cost is strongly reduced compared to a battery that can handle all the trips but the amount of energy from fast charging is low compared to the total energy. In the coming subsection EDDs with different shapes are investigated.

4.3 Studies of Different Energy Distribution Diagrams

In this subsection the number of operation days are set to $N_{op} = 1750$ which corresponds to a truck that operates five days per week, 50 weeks per year in seven years. All the analysis in this subsection was done under the assumptions that the battery capacity and the power of the charger are assumed to be continuous variables in the span from zero to arbitrary high values and that it is possible to charge exactly when it is needed.

In this thesis three different energy distribution diagrams are investigated namely, the rectangular EDD, the triangular EDD and the two-step rectangular EDD defined below. Let $E(N)$ be the total amount of energy consumed by a truck day N. That means, $E(N)$ determines the envelope of the EDD and is, therefore, called the energy function. For the rectangular EDD the energy function is expressed as

$$E(N) = E_{max}, \qquad N \in [0, N_{op}], \tag{4.6}$$

where E_{max} is the highest daily energy consumption over the truck's service life. For the triangular EDD the energy function is

$$E(N) = -\frac{E_{max}}{N_{op}} N + E_{max}, \qquad N \in [0, N_{op}]. \tag{4.7}$$

For the two-step rectangular EDD the energy function is written as

$$E(N) = \begin{cases} E_{max}, & N \in [0, M] \\ E_{min}, & N \in (M, N_{op}], \end{cases} \tag{4.8}$$

where E_{min} is the lowest daily energy consumed for the truck and M is the number of days the truck consumes the maximum daily energy E_{max}. Figure 4.2 shows the above-mentioned energy distribution diagrams, where the upper left-hand part of the figure shows the rectangular EDD, the upper right-hand part of the figure shows the triangular EDD and the lower middle part of the figure shows the two-step rectangular EDD. The number of days with fast charging, the amount of public fast charging and the energy charged from the private depot charger are marked in the three diagrams for a certain useful battery capacity. This is possible to determine since the battery is fully charged in the morning and fast charging only is carried out if it is necessary. Further, fast charging is assumed to be available exactly when it is needed and one only charges the amount of energy needed to reach the privet depot charger again. Thus, these calculations are done under the assumption that one has perfect information about the future energy consumption.

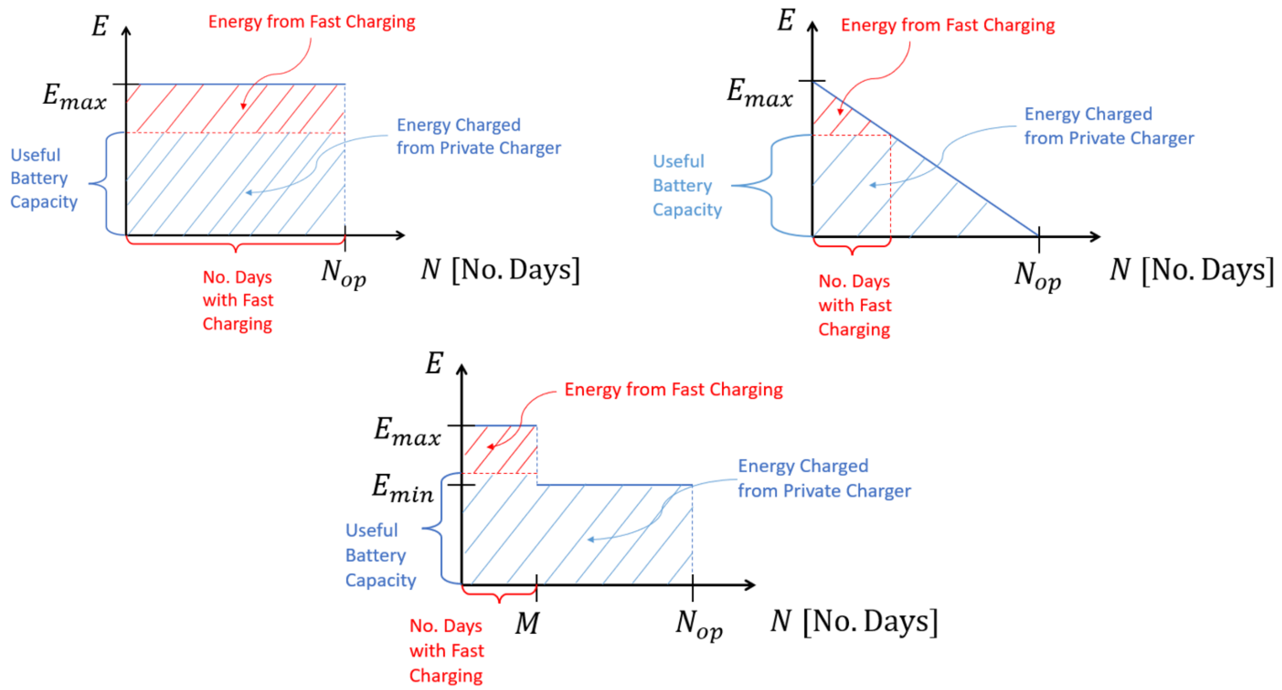

Figure 4.2: Three types of energy distribution diagrams. The upper left-hand part of the figure shows the rectangular EDD, the upper right-hand part of the figure shows the triangular EDD and the lower middle part of the figure shows the two-step rectangular EDD. The number of days with fast charging, the amount of public fast charging and the energy charge from the private charger are marked in the sub figures for a certain useful battery capacity.

By considering Equation 4.1 one realizes that for a fixed set of cost parameters and a certain EDD there are three parameters that could be affected to minimize the cost, namely r_{ch}, B_c and P_{ch} or equivalent r_{ch} and the utilisation factors. However, these three are strongly connected. For a certain battery capacity, one finds the cheapest charger by selecting the charger power so it just can charge the whole useful battery capacity over the night. In this thesis the available charger time is named T_{ch} and is set to 14 hours. The amount of private charging follows from the shape of the EDD and the choice of the useful battery capacity, see the blue striped areas in the right-hand part of Figure 4.1 and in Figure 4.2, which then gives r_{ch}. This follows from the fact that one does not want to charge with public fast chargers more than necessary for a given battery capacity. So, for a given EDD the most cost effective P_{ch} and r_{ch} can be seen as a function of the battery capacity. Hence, the cost function can now be seen as a function of just one variable, for example B_c, and can then be optimized by methods from calculus in one dimension. Due to battery ageing and robustness margins, it is assumed that only a share of the battery capacity, r_{SoC}, can be used. The useful battery capacity, B_{cu}, can then be expressed as

$$B_{cu} = r_{SoC} \cdot B_c, \tag{4.9}$$

where r_{SoC} is set to 80 % in this subsection.

To demonstrate the above reasoning how the EDD can be used for selecting the optimal battery capacity the rectangular EDD will now be studied. For a given battery capacity B_c the charger power follows as

$$P_{ch} = \frac{B_{cu}}{T_{ch}} = \frac{r_{SoC} \cdot B_c}{T_{ch}} \tag{4.10}$$

since the smallest charger available to charge the whole useful battery capacity in one night is chosen. Further, r_{ch} follows with support from the upper right-hand part of Figure 4.2 according to

$$r_{ch} = \frac{B_{cu} \cdot N_{op}}{E_{max} \cdot N_{op}} = \frac{r_{SoC} \cdot B_c}{E_{max}}, \tag{4.11}$$

due to that one minimises the public fast charging for a given battery capacity. The battery utilisation is now given by

$$\Gamma_b = \frac{E_{tot}}{B_c} = \frac{E_{max} \cdot N_{op}}{B_c} \tag{4.12}$$

and the charger utilisation can be written as

$$\Gamma_{ch} = \frac{E_{ch}}{T \cdot P_{ch}} = \frac{r_{SoC} \cdot B_c \cdot N_{op}}{T \cdot P_{ch}}. \tag{4.13}$$

If r_{ch}, the utilisation factors and P_{ch} are inserted in Equation 4.5 one obtain

$$\begin{aligned} f_{BEV} &= r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\Gamma_b} + \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}} \\ &= \frac{r_{SoC} \cdot B_c}{E_{max}} \cdot C_e + (1 - \frac{r_{SoC} \cdot B_c}{E_{max}}) \cdot C_{epub} + \frac{C_b}{\frac{E_{max} \cdot N_{op}}{B_c}} + \frac{\frac{r_{SoC} \cdot B_c}{E_{max}} \cdot C_{ch}}{\frac{r_{SoC} \cdot B_c \cdot N_{op}}{T \cdot P_{ch}}} \\ &= \left(\frac{r_{SoC}}{E_{max}} \cdot C_e - \frac{r_{SoC}}{E_{max}} \cdot C_{epub} + \frac{C_b}{E_{max} \cdot N_{op}} + \frac{r_{SoC} \cdot T \cdot C_{ch}}{E_{max} \cdot T_{ch} \cdot N_{op}} \right) \cdot B_c + C_{epub}. \end{aligned} \tag{4.14}$$

As seen from the above equation the cost function is now a function of only the battery capacity, and it can be minimised by methods from one-dimensional calculus. The derivative is given by

$$\frac{df_{BEV}}{dB_c} = \frac{r_{SoC}}{E_{max}} \cdot C_e - \frac{r_{SoC}}{E_{max}} \cdot C_{epub} + \frac{C_b}{E_{max} \cdot N_{op}} + \frac{r_{SoC} \cdot T \cdot C_{ch}}{E_{max} \cdot T_{ch} \cdot N_{op}} \tag{4.15}$$

and by inserting the values for the parameters and using the fact that $E_{max} > 0$ one obtains

$$\frac{df_{BEV}}{dB_c} < 0 \tag{4.16}$$

which implies that the cost decreases with increasing values on B_c. One therefore concludes that the battery capacity should be selected as large as possible. So, the cost function reaches its minimum value when

$$B_{cu} = E_{max} \iff B_c = \frac{E_{max}}{r_{SoC}}, \tag{4.17}$$

this gives the value of the cost function of

$$f_{BEV} = C_e + \frac{C_b}{r_{SoC} \cdot N_{op}} + \frac{C_{ch}}{\frac{T_{ch}}{T} \cdot N_{op}} = 0.26\ \text{€/kWh} < C_d = 0.30\ \text{€/kWh}. \tag{4.18}$$

From the above expression one may notice several things. Firstly, the value of the cost function is below the reference value, C_d, for diesel. This means that the battery electric truck is cost competitive for a rectangular EDD, i.e. when the variation in the daily energy consumption is low. Secondly, the battery should be sized so it can handle the whole energy consumption for the day. This means that public fast charging is excluded and the price for public fast charging does not either influence the value of the cost function, seen from the expression above. Further one notices that the cost increases with increasing values on the cost parameters which is intuitive. The battery cost decreases if a larger share of the battery capacity can be used and the charger cost decreases if the charger is used a larger share of the total time. The cost is independent of the maximum energy consumption for a day since E_{max} is not visible in the above expression. Finally, the cost is decreasing for increasing values of the number of operation days, in the (surreal) case when the number of operational days tends to infinity the value of the cost function approaches the cost for electricity. Worth mentioning is that the rectangular EDD is the best one suitable for electrification. This might feel intuitive and can be explained by that the battery can be sized to handle the energy needed for all the days without public fast charging and without being unnecessary large for any day. Even the depot charger can be sized to have maximum utilisation. In reality, there will not be any trucks with exactly a rectangular shape of the EDD. However, since many trucks have the same or similar transport task every day there are many EDD that are approximately rectangular.

Even the triangular and two-step rectangular EDD has been studied in similar way as shown above. The mathematical steps are shown in Paper A. In the case with the triangular EDD the electric truck is not competitive with the diesel truck with the price parameters used in this thesis. A triangular EDD means that the truck consumes different amounts of energy each day. Luckily this shape of EDD is rare for commercial trucks.

In case of a two-step rectangle EDD the electric trucks can, in many cases, compete with diesel trucks. With this EDD the lowest cost is obtained by either having a battery so large that it can handle all the trips without fast charging, or a battery that just can handle the low consuming trips without fast charging. If the days with high consumption are sufficiently many, one should choose the large battery, otherwise the small. In this context sufficiently many are a little less than 1000 days. In this case, the EDD best suited for the electric trucks are the ones close to a single rectangle or a rectangle with a thin peak on top. The last-mentioned case corresponds to a truck that consumes all most the same amount of energy all days but with a small share of days with higher consumption. In this case it is possible to size the battery for the low consuming days, just to a small cost for public fast charging for the high consuming days. The worst EDD is the ”L”-shaped one, if the peak is not really thin, and the EDD that has a long thin tail. The "L"-shaped EDD corresponds to a truck with many low consuming days and some days with clearly higher consumption. From the results one knows that one should select the small battery resulting in high battery utilisation but in this case the share of public fast charging becomes high which explains the bad cost effectiveness. Also worth mentioning is that this charging strategy could be problematic since it means that one has to use fast charging several times during the high consuming trips. A truck with two different transport tasks has an EDD that is approximately of the type two-step rectangular. In Paper A the parameter $r = \frac{E_{min}}{E_{max}}$ is introduces to facilitates the investigation of all two-step rectangle EDD. In the left-hand side of Figure 4.3 one may see the value of the cost function in the $M - r$ space. The right-hand part of the figure illustrates how the shape of the two-step rectangle EDD looks for different values on M and r. In the area enclosed by the red curve and the $M-$axis the diesel truck has a lower cost than the battery electric one. Keep in mind that this area depends on the selected values on the cost parameters.

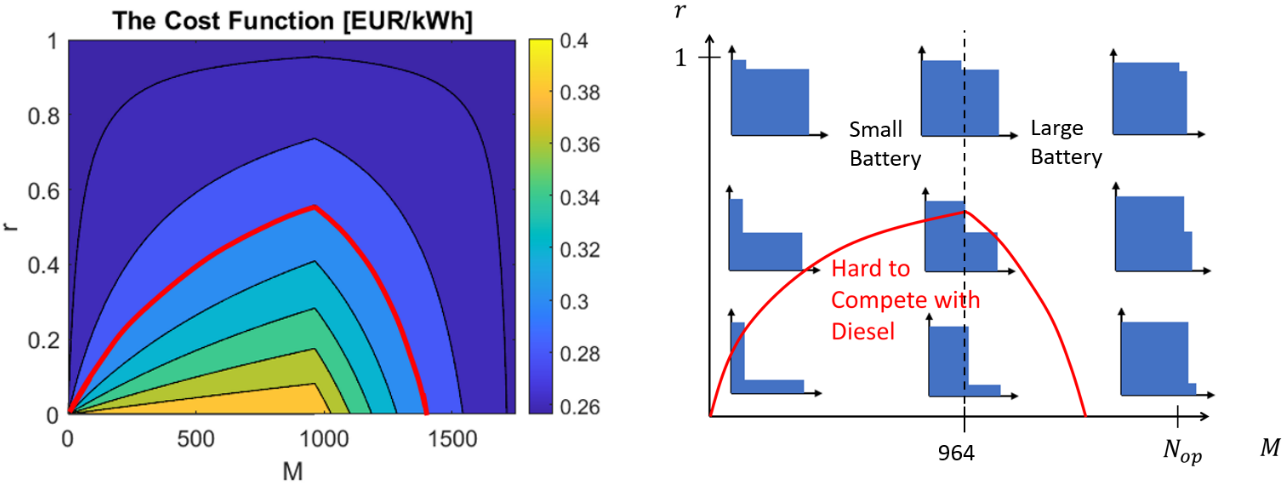

Figure 4.3: The cost function as a function of M and r in the left-hand part of the figure. The battery electric trucks are more expensive than the commercial diesel ones in the area enclosed by the red curve and the M-axis. The right-hand part of the figure shows how the shape of the EDD depends on the parameters M and r. If there is an EDD on or to the left of the dashed vertical black line, the smaller battery is the most cost-efficient and, to the right of it, the larger battery.

Even for the two last mentioned shapes of the EDD the cost decreases with increasing number of operation days. Therefore, it is interesting to find a limit to how many operation days that is necessary for the electric truck to be more cost effective than the diesel option. Since a lower limit shall be found one selects the best suited EDD for electrification, namely the rectangular one and solve the equation

$$f_{BEV} = C_d. \tag{4.19}$$

One may now use the equation 4.18 which gives the solution $N_{op} = 1402$. One concludes that the electric truck has to operate at least 1400 days to be cost competitive with a diesel truck.

4.4 Sizing the Battery for an Arbitrary Driving Pattern

The selected shapes of the EDD can approximate most of the possible EDDs and give insights as to which EDD shapes are best suited to electric trucks. However, for a specific EDD, it may be necessary to determine the most cost-efficient battery size of that particular EDD rather than just the best battery size for an approximation of it.

As mentioned earlier, the choice of B_c directly determines r_{ch} and P_{ch}. Thus, a battery capacity may be chosen which determines r_{ch} and P_{ch} and the corresponding cost function value. By systematically testing enough battery capacity values, the most cost-efficient battery capacity can be selected. The most cost-efficient battery capacity will depend on the energy function. This insight allows us to establish an algorithm to determine the most cost-efficient battery capacity for an EDD with an arbitrary energy function $E(N)$. The algorithm follows below.

Algorithm Description

1. Choose a sufficiently small battery capacity value, such as B_{c1}.
2. Compute the total energy, $E_{tot} = \int_{0}^{N_{op}} E(N)dN$.
3. Find the smallest N_1 so that $r_{SoC} \cdot B_{c1} = E(N_1)$. The number of days needed to fast charge is N_1.
4. Compute
   (a) $r_{ch} = \frac{r_{SoC} \cdot B_{c1} \cdot N_1 + \int_{N_1}^{N_{op}} E(N)dN}{E_{tot}}$,
   (b) $\Gamma_b = \frac{E_{tot}}{B_{c1}}$
   and
   (c) $\Gamma_{ch} = \frac{r_{ch} \cdot E_{tot}}{\frac{r_{SoC} \cdot B_{c1}}{T_{ch}} \cdot T}$.
5. Compute $f_{BEV1} = f(B_{c1})$ from Equation (4.5).
6. Set $B_{c2} = B_{c1} + \Delta B_c$, ΔB_c should be sufficiently small.
7. Repeat steps 3-6 but increase each index by one until $r_{SoC} \cdot B_{c(n+1)} > E_{max}$, then set $r_{SoC} \cdot B_{c(n+1)} = E_{max}$, repeat steps 3-5 and then jump to step 8.
8. One now has the cost per kWh of propulsion energy expressed as a function of battery capacity. Select the battery capacity that gives the lowest cost.

4.5 Application of Theory, Electrification of Long-Haul trucks

So far, the theory has only been demonstrated in a general way. Now the developed theory will be applied to a fictitious but realistic haulage company that would like to electrify their diesel trucks. The analysed case is designed to represent typical line-haul between terminals in a big logistic system and is strongly inspired by the Swedish haulage company "Tommy Nordbergh Åkeri ab". The studied haulage company has a fleet of trucks and has the ambition to replace all of them with battery electric ones. The economic consequences will now be investigated under the assumption that there will be no changes in how the trucks operate. The description of the transport task follows below.

The company has two terminals, Terminal A and Terminal B, which are connected with a highway. Terminal A is located in the city Helsingborg at the Swedish west coast and Terminal B in Stockholm, the capitol of Sweden, located on the east coast. Five times per week the following procedure is repeated. Half of the trucks arrive at Terminal A and half of the trucks arrive at Terminal B in early afternoon after some local distribution tasks during the day. Then the trucks stand still for a certain time, T_1, and thereafter leave the terminal and drive towards the other terminal. The trucks leave the terminal, one by one, with a certain time gap, T_{gap}. Midway between the terminals the drivers have a mandatory break of length T_{break} at a rest area. After the break each driver from Terminal A changes truck with a driver from Terminal B and then returns to their home terminal. After arrival, the trucks stand still for a certain time T_2. Further, let the distance between Terminal A and Terminal B be S, the trucks mean speed $\overline{v}$, the trucks mean energy consumption per unit distance travelled $\frac{\Delta E}{\Delta x}$ and the number of trucks starting from *each* terminal N_{trucks}. During the local distribution tasks, which take place during the day, each truck drives a distance $S/2$. The notation for the parameters and their values used in this thesis are listed in Table 4.3. In addition to driving each weekday during the year, during the weekends the trucks perform on average 50 extra night trips per year and truck. At the rest area a charge-point operator is planning to build public fast chargers, so in addition to the company's private chargers at each terminal the trucks can also be charged at the rest area by the public fast chargers.

Table 4.3: Notations for the different parameters and their value used in this thesis.

Parameters	**Notation**	**Value**
Time Gap Between Trucks	T_{gap}	7 minutes
Inactive Time for the Trucks in the Afternoon	T_1	2 h
Time for the Break	T_{break}	45 minutes
Inactive Time for the Trucks in the Morning	T_2	4 h
Distance Between the Terminals	S	550 km
Mean Speed of the Trucks	$\overline{v}$	75 km/h
Energy Consumption	$\frac{\Delta E}{\Delta x}$	1.5 kWh/km
Numbers of Trucks Starting from Each Terminal	N_{trucks}	30

Equation 4.5 will be used to determine the value of the cost function, with the same parameter values as earlier, with the exception that r_{SoC} is adopted so that the battery can perform the needed number of charging cycles over the trucks service life. The number of possible charging cycles for a modern lithium battery is assumed to depend on r_{SoC} according to the table in the left-hand part of Figure 4.4. The exact number of lifetime cycles varies for different types of Li-ion cells, but the general trends are the same, that is, the number of cycles increases faster than the decrease in cycle depth, resulting in a higher total life-energy throughput for smaller values on r_{SoC}. This can be seen in studies such as [68]. Since the needed number of cycles for the haulage companies trucks likely not matches the table values a power function $g(r_{SoC}) = a \cdot {r_{SoC}}^b$ where $a \approx 2000$ and $b \approx -1.9$ is fitted to the table values, see the right-hand part of Figure 4.4. Thus, the function g gives the possible number of charging cycles for each value of r_{SoC}.

r_{SoC}	**No. Possible Charging Cycles**
0.2	40,000
0.4	10,000
0.6	5000
0.8	3000
1	2000

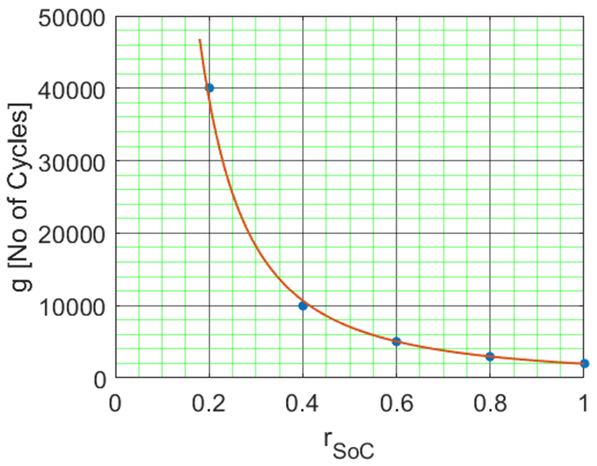

Figure 4.4: The left-hand side shows the number of possible charging cycles for a modern lithium battery depending on the parameter r_{SoC}. The right-hand side shows a power function $g(r_{SoC})$ is fitted to the table values which are indicated with blue dots.

The cost function expresses the cost for just *one* truck with *one* private charger. However, even if the company has many trucks there is no problem using the introduced cost function since it is assumed that there are as many private chargers as trucks. From the description of the transport task, one knows that the trucks' EDD will be of the type two-step rectangular. Since the trucks perform local distribution five times per week during their seven year-long service life the number of day trips becomes 1820. There will be equally many night trips plus 50 extra night trips per year, resulting in 2170 night trips. The night trips will consume the energy $S \cdot \frac{dE}{dx} = 825$ kWh and the corresponding value for the day trips will be $\frac{S}{2} \cdot \frac{dE}{dx} = 412.5$ kWh. The EDD for each truck is shown in Figure 4.5.

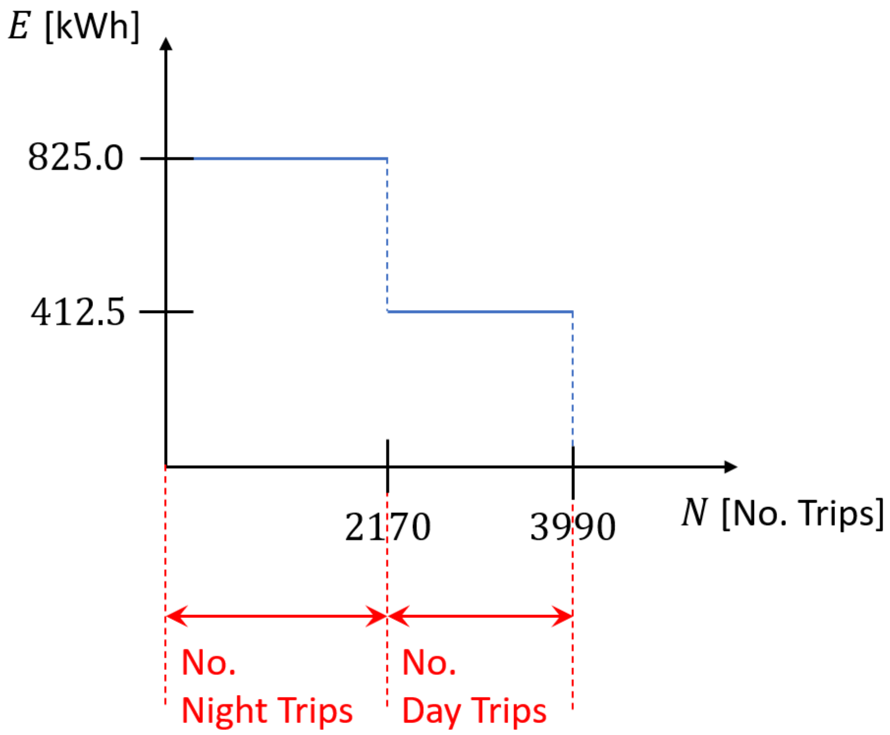

Figure 4.5: The energy distribution diagram for each truck.

Even though the prerequisites are not exactly the same as when the general theory was presented it is still reasonable to believe that the battery should be sized either so it just can handle the low consuming trips without public fast charging or so it can handle all trips without fast charging. These two cases will now be investigated.

Firstly, the case with the small battery. The charging strategy will be as follows. The truck will charge the whole useful capacity after the local distribution during the time T_1. Then it will use the same amount of energy during the first half of its night trip, re-charge using public fast chargers during the mandatory break of length T_{break} and then empty the battery once again and re-charge in the time T_2. Since the useful capacity will be chosen to 412.5 kWh the battery will in total have to preforms $2 \cdot 2170 + (3990 - 2170) = 6160$ cycles, since there are 2170 night trips and 3990-2170 day trips, see Figure 4.5. To size the battery for this mission one needs to solve the equation

$$g(r_{SoC}) = 6160 \implies r_{SoC} \approx 0.54. \tag{4.20}$$

Thus, the battery capacity is given by

$$B_c = B_{cu}/r_{SoC} \approx 770\text{kWh}. \tag{4.21}$$

Since the useful battery capacity is known one may find r_{ch} according to

$$r_{ch} = \frac{E_{ch}}{E_{tot}} \approx 0.65, \tag{4.22}$$

where $E_{ch} = 412.5$ kWh $\cdot\, 3990 \approx 1.6 \cdot 10^6$ kWh and $E_{tot} = 825$ kWh $\cdot\, 2170 + 412.5$ kWh $\cdot\, (3990 - 2170) \approx 2.5 \cdot 10^6$ kWh, see the EDD in Figure 4.5. The battery utilisation can be found by dividing the total energy that passes through the battery during its service life with the battery capacity according to

$$\Gamma_b = \frac{E_{tot}}{B_c} = 3316 \text{ EFC}. \tag{4.23}$$

This value is high for a battery in an electric truck (which is good). The private depot charger shall be able to charge the useful battery capacity during the time T_1 och T_2. Thus,

$$P_{ch} = \frac{B_{cu}}{\min(T_1, T_2)} \approx 210 \text{ kW}. \tag{4.24}$$

Now the charger utilisation can be determined

$$\Gamma_{ch} = \frac{r_{ch} \cdot E_{tot}}{P_{ch} \cdot T} \approx 13\%. \tag{4.25}$$

By inserting the above results in Equation 4.5 one finds

$$f_{BEV} = 0.32\,\text{€/kWh}. \tag{4.26}$$

Secondly, the value of the cost function can be calculated for the case with a large battery. By calculations in a similar way as above one finds that

$$f_{BEV} = 0.24\,\text{€/kWh}. \tag{4.27}$$

The mathematical steps can be followed in Paper B. So, in the case of the small battery the electric trucks seem to be a bit more expensive than the diesel ones, but the large-battery strategy seems to be more cost effective than the diesel option. However, especially the large-battery strategy can cause costs due to significant loss in payload capacity caused by the heavy battery. Even for the small battery there is a loss in payload capacity compared to the diesel trucks. For explicit calculations, please see Paper B. It is important to emphasise that a loss in payload capacity does not automatically result in an extra cost. It depends on the density of the goods and if the trucks are filled. The value of the cost function for the small-battery case is found under the assumption of expensive public fast charging, 0.4 €/kWh. The studied company likely wants to use the small-battery solution if the cost for fast charging is so low that the cost functions value would be the same as for the large battery, since it would result in a lower risk for extra cost due to loss in payload capacity. It is therefore interesting to investigate if the charge point operator can lower the price. The costs for the charger owner are the cost for the electricity, and the charger and the grid connection. The cost for the charger and the grid connection is assumed to be proportional to the power of the chargers and the cost per kWh, f_{ch}, is expressed in a similar way as in Section 4.1

$$f_{ch} = C_e + \frac{C_{ch} \cdot P_{ch} \cdot T}{E_{ch}} = C_e + \frac{C_{ch}}{\Gamma_{ch}}. \tag{4.28}$$

From the above equation one notice that the cost decreases with increasing charger utilisation. This means that the price for public fast charging could be low if the utilisation is high. Therefore, the possible utilisation is investigated.

First, one may assume that the treated haulage company will charge each truck fully at the rest area. The drivers have a break of 45 minutes, so one knows that each truck will charge for 45 minutes. So how many chargers are needed? The 30 trucks from each terminal depart with a time gape $T_{gap} = 7$ minutes since the terminal personnel and gates do not have the capacity of sending them off at the same time. The first two trucks leave Terminal A and B at 6 PM, then drive the distance $S/2 = 275$ km to the rest area with the mean speed 75 km/h, and charge for 45 minutes when they arrive at the rest area. The drivers switch truck with the driver from the other terminal and then return home. The number of charging trucks as a function of time can be found from a simulation. However, one cannot expect perfect timing, so the trucks are assumed to sometimes be delayed. For the company delays of over 15 minutes are rare. Therefore, the delay for each truck is the magnitude of a random number drawn from a normal distribution with expected value 0 minutes and standard deviation 5 minutes. The left-hand part of Figure 4.6 shows the number of charging trucks at the rest area as a function of time, for one night. It can be seen that the maximum number of chargers needed on this day is 15. The right-hand part of Figure 4.6 shows a histogram where the value on the x-axis represent the maximum chargers needed on one day and the height of the bar represent how many days that occurs on a 10-year period[2]. As seen from the histogram, one needs to have 16 chargers at the rest area, with the selected model and parameter settings. The fact that it sometimes is a demand for 17 chargers is not seen as a problem since this happens only twice in a year. The result does *not* change dramatically when one changes the standard deviation by ±2 minutes.

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[2] The trucks operate almost 6 nights per week.

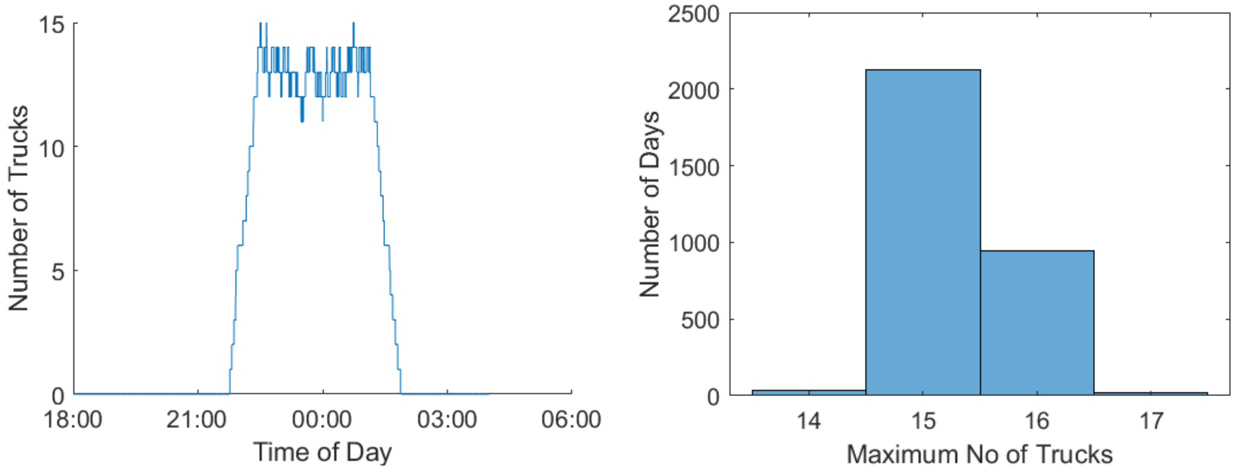


Figure 4.6: The left-hand part of the figure shows the number of charging trucks at the rest area as a function of time for one day. The right-hand part of the figure shows how many days over a 10-year period a certain number of chargers is needed.

Each of the 16 chargers must be able to charge the trucks whole useful battery capacity in the time T_{break}. Thus

$$P_{ch} = \frac{B_{cu}}{T_{break}} = \frac{412.5\text{ kWh}}{0.75\text{ h}} = 550\text{ kW}. \tag{4.29}$$

Assuming only the haulage company uses these chargers, the charger utilization can be calculated since the charging need of the trucks and number of chargers are known

$$\Gamma_{ch} = 10\ \%. \tag{4.30}$$

So, if the company that installs the chargers have no other customers than the analysed company the cost for the chargers will, according to Equation 4.28, be

$$f_{ch} = 0.21\ €/\text{ kWh}. \tag{4.31}$$

Consequently, it seems to be possible to lower the price from the originally assumed 0.4 €/kWh. So, how low does the price have to be if the haulage company shall consider the small battery and fast charge the whole useful capacity at the rest area? The company will probably select the smaller battery if it is possible to reach an equally low value of the cost function as for the large battery, due to less loss in payload capacity. Thus, one may determine the required price for fast charging by solving the equation

$$f_{BEV} = 0.24\ €/\text{kWh}, \tag{4.32}$$

with the values for the small battery. To proceed

$$C_{epub} = \frac{0.24\ €/\text{kWh} - r_{ch} \cdot C_e - \frac{C_b}{\Gamma_b} - \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}}{1 - r_{ch}} = 0.17\ €/\text{kWh}. \tag{4.33}$$

At first this seems hard to reach since the value is below the cost of the charger owner, according to Equation 4.31. However, as seen from Equation 4.28 the normalised cost for the charge point operator only depends on the charger utilization factor. Figure 4.7 shows f_{ch} as a function of Γ_{ch}.

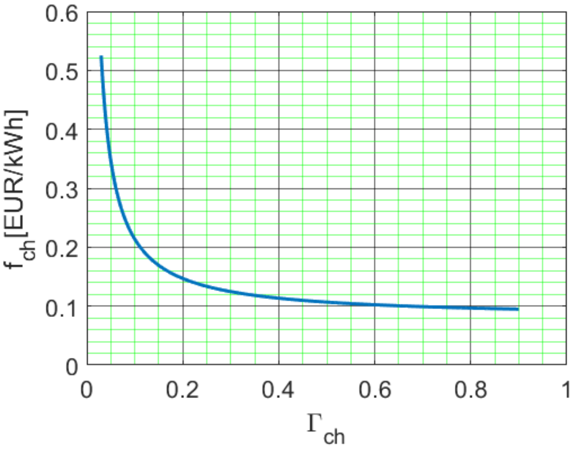


Figure 4.7: The normalised cost f_{ch} as a function of the charger utilization factor, Γ_{ch}.

From the figure one observes that the value of f_{ch} is below 0.17 €/kWh for charger utilization factors of 15% or more. The treated haulage company will utilise the chargers by 10% during the night. It seems possible to have at least the same use of the chargers during the day by other companies. In this case the charger utilization factor will be 20 % which by Equation 4.28 leads to $f_{ch} = 0.15$ €/kWh, allowing some profit also at a price of only 0.17 €/kWh . If one in addition has other customers in the morning, afternoon and evening it might be possible to reach a charger utilization factor of 25%. Such a utilization factor will lead to $f_{ch} = 0.13$ €/kWh and then the chargers can provide a profit also with as low price as only 0.17 €/kWh.

In case of a low price for fast charging of 0.17 €/kWh and selecting the small-battery, the haulage company will have a normalised cost for battery electric propulsion of 0.24 €/kWh of which the cost for the private charging is 0.05 €/kWh, the cost for the public fast charging is 0.06 €/kWh, the cost for the battery is 0.06 €/kWh while the cost for their own chargers and their grid connection is 0.07 €/kWh. The indirect cost for any loss in payload capacity will probably be low with the small battery. The calculations done in this thesis strongly indicate that the electric trucks will be more cost efficient than the commercial diesel trucks, for haulage companies with similar driving patterns to the treated company. Figure 4.8 compare the cost per propulsion kWh for the small battery and expensive fast charging, the large battery and the small battery with cheap fast charging with the diesel cost as a reference. Note that the potential cost for losing pay load capacity due to a large battery is not included.

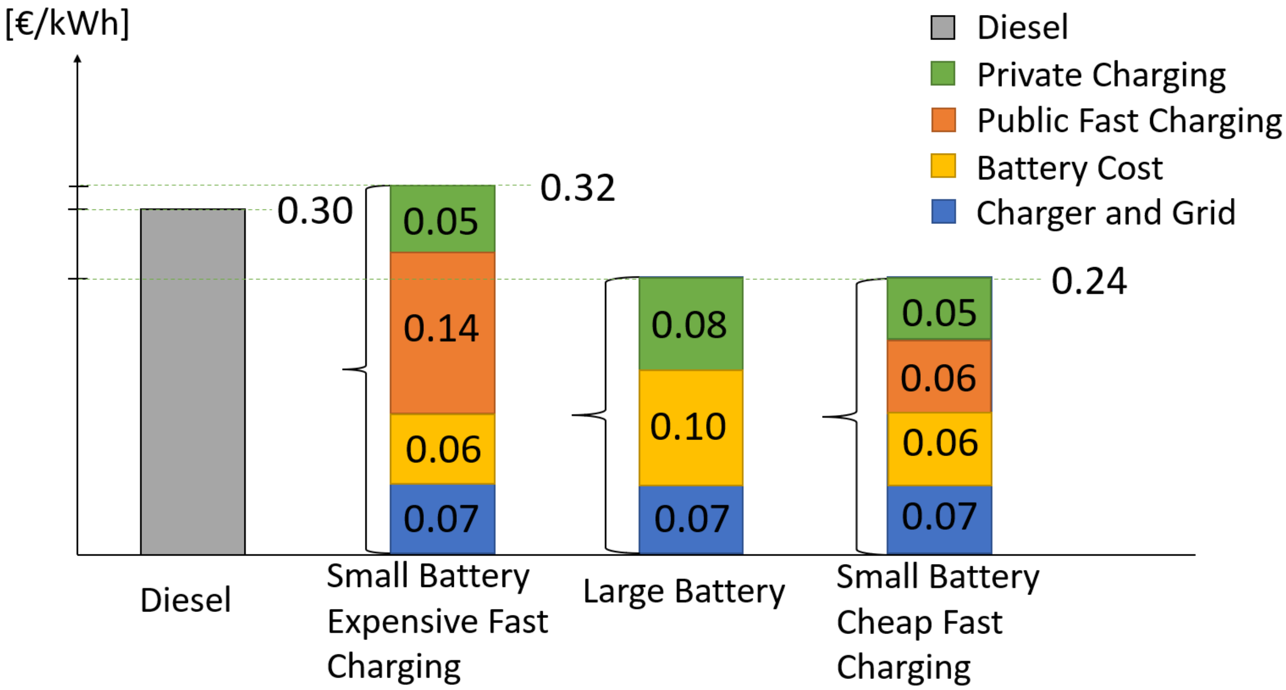


Figure 4.8: The different cost for the alternative strategies for the haulage company. The height of the bars represents the total cost for one strategy. The colours show the individual costs according to the legend. All numbers are in €/kWh. (Due to rounding the individual cost for the battery electric truck with the large battery seems to add up to more than the total cost.)

As seen above, the battery electric trucks could, with the right driving patterns, be cost competitive to commercial diesel trucks. Also, it is shown that the price for public fast charging is crucial for the cost effectiveness and charging strategy of battery electric long-haul trucks. As found, a prerequisite for cheap public fast charging is high utilisation of the chargers. However, high utilisation increases the risk of severe queues since a charger with high utilisation rarely is free. Therefore, the remaining parts of the thesis will focus on possible utilisation of public fast chargers and estimates of charging prices and queuing problems at fast charging stations under competition between CPOs.

4.6 Possible Utilisation of and Queues at Public Fast Charging Stations

In this section the possible charger utilisation while avoiding long queues at the charging stations will be investigated along a Swedish highway. The case under analysis is the highway between the Swedish cities Helsingborg on the west coast and the capital Stockholm on the east coast under the assumption of full electrification of the truck fleet. The system is investigated using an agent-based model where the traffic flow is intended to be representative of a typical weekday. The highway between Helsingborg and Stockholm is called E4. The road is 553 km long and marked with blue in the map in Figure 4.9.

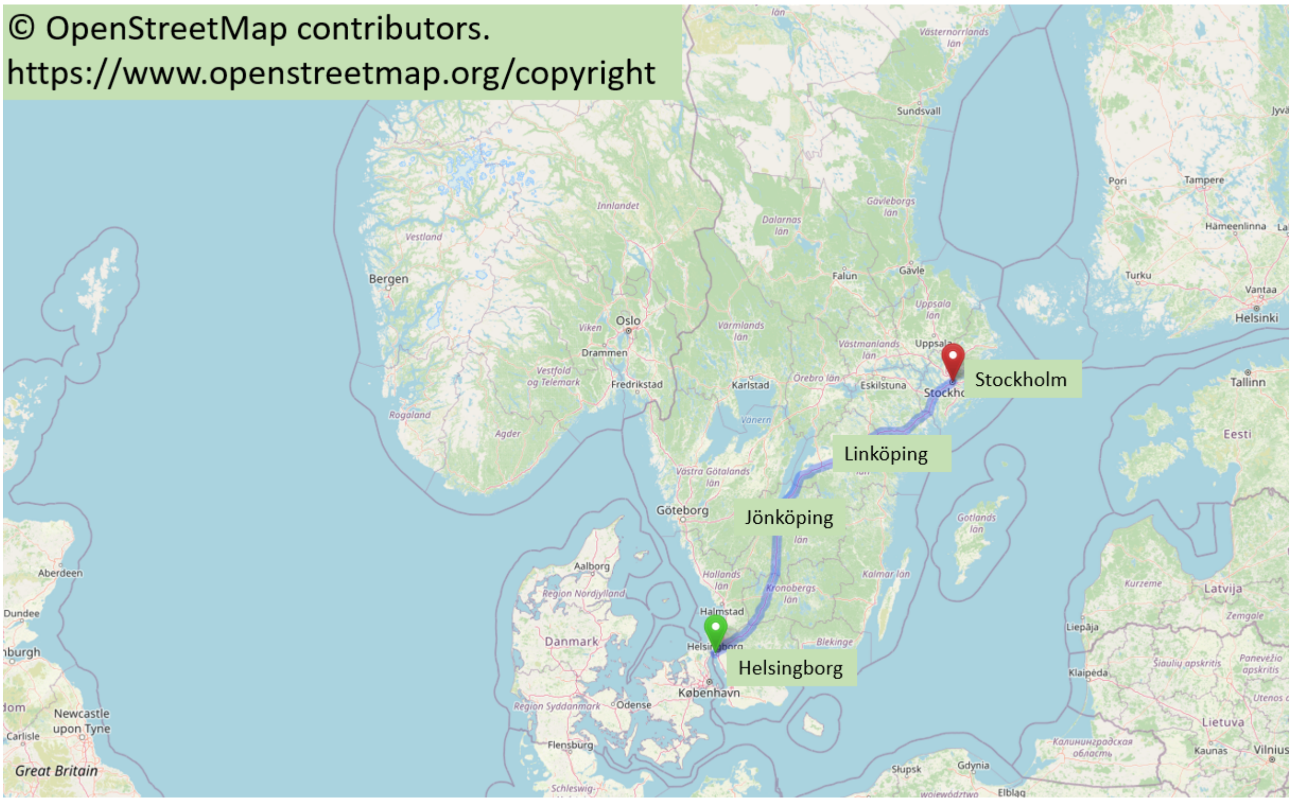


Figure 4.9: The highway between Helsingborg and Stockholm marked with blue.

The method used to analyse the utilisation is to create an agent-based model in which the trucks select charging station along the road such that they avoid large queues and high prices. As a first step, a representative traffic flow of trucks is created defining each trucks departure place, time and SoC (state of charge) along with its destination and required SoC at the destination. It is assumed that trucks can only enter or leave the highway where roads with considerable traffic flow of trucks connect to the highway. Since the cities Mjölby, Linköping and Norrköping are quite close to each other they are seen as one city located in Linköping. The road is divided into three sections, where Section 1 starts at Helsingborg and ends at Jönköping, Section 2 starts at Jönköping and ends at Linköping and Section 3 starts at Linköping and ends at Södertälje/Stockholm, which is considered as one city located in Stockholm. Data on the real-world truck flow has been available at the communities Ljungby, Gränna and Tystberga [69] which are located in Section 1, 2 and 3 respectively. Trucks without trailers are excluded from the data since they probably do not travel long distances and therefore do not use public fast charging. In Table 4.4, the distances from Helsingborg to the cities and communities are listed, and the traffic flows from data are shown in Figure 4.10 in which the traffic flows are expressed in trucks per day, which has been averaged over a year. The outward direction is defined from Helsingborg to Stockholm according to Figure 4.10. The black arrows represent the flows along the way, and the red arrows show the flow of trucks that enter or leave the highway.

Table 4.4: Distance from Helsingborg to the cities and communities.

City/Community	Position [km]
Helsingborg	0
Ljungby	134
Jönköping	228
Gränna	265
Mjölby/Linköping/Norrköping	355
Tystberga	470
Södertälje/Stockholm	553

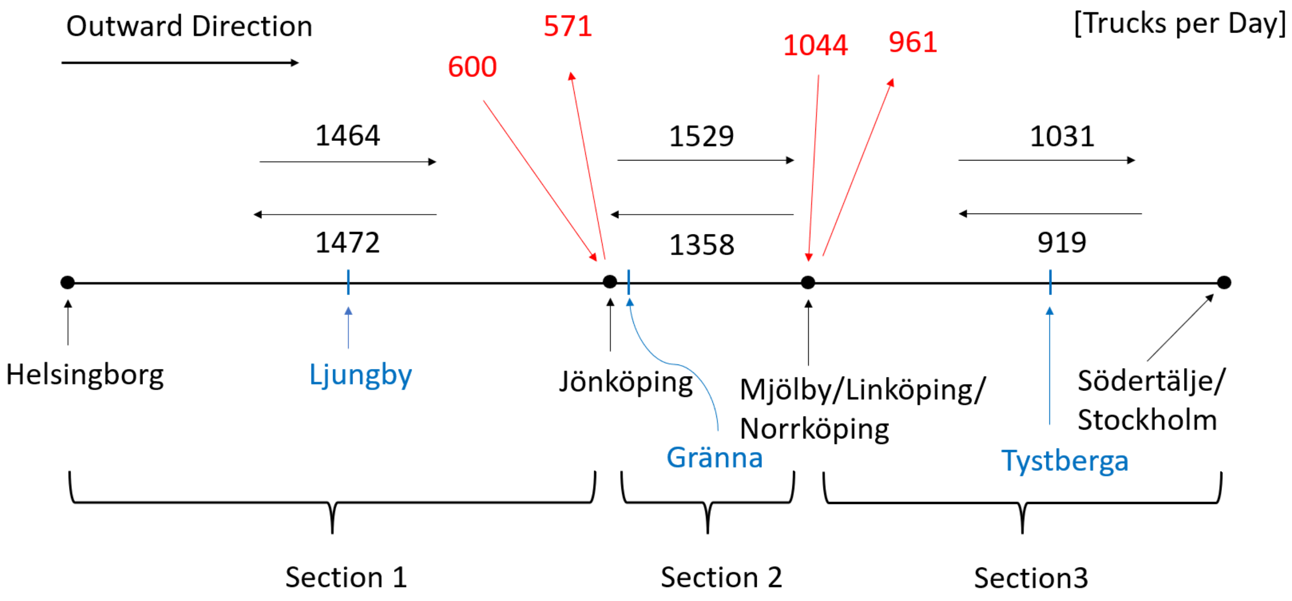


Figure 4.10: The traffic flows on the segments of the road and the traffic flows that enter or leave the road (red arrows). The flows are given in trucks per day. Outward direction is defined from Helsingborg towards Stockholm.

Based on the data in Figure 4.10 the truck flows between the different cities are constructed, with the aim of representing a typical day. The flows are shown in Table 4.5 and agrees with the total flows along the highway (the black arrows) presented in Figure 4.10.

Table 4.5: The origin and destinations for the trucks.

Start (No. trucks)	**Destination (No. trucks)**			
	Helsingborg	**Jönköping**	**Linköping**	**Stockholm**
Helsingborg 1464	-	381	520	563
Jönköping 909	463	-	221	225
Linköping 1063	621	199	-	243
Stockholm 919	388	150	381	-

For some days traffic-flow data, expressed as trucks per hour, was available each hour. The departure time of the trucks in the simulation was selected randomly according to a distribution to resemble the actual time variation in the data. The result can be seen in Figure 4.11. The model flows shown in the figure are the flows when the trucks do not stop and charge. However, since many of the trucks will charge, the traffic flow in the simulations will not be exactly the same.

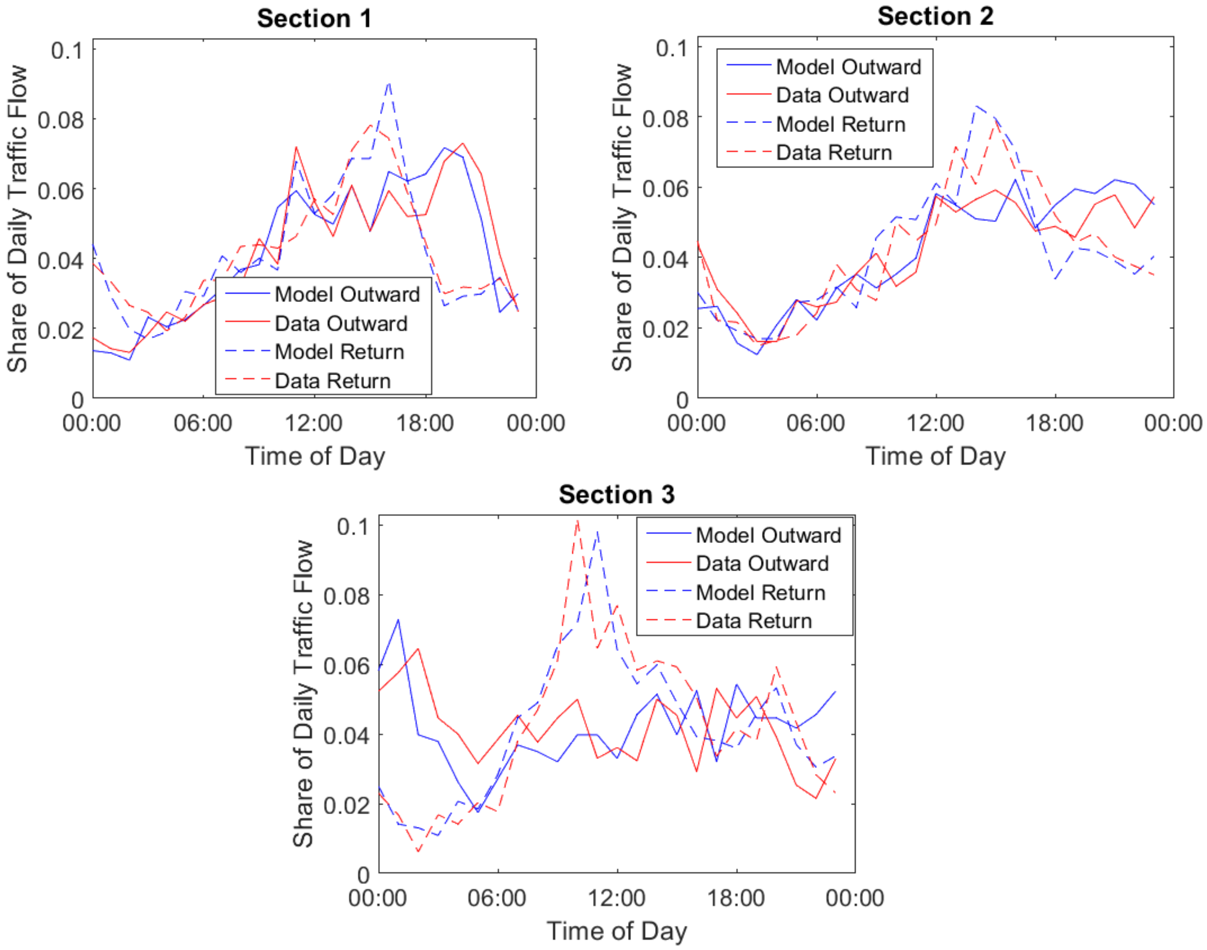


Figure 4.11: The share of the daily traffic flow for each road section in the outward (solid) and return (dashed) direction. The red curves correspond to the data, and the blue correspond to the modelled flow if the trucks always drive at constant speed $v = 75$ km/h without charging.

The initial value of the battery SoC for each truck is drawn from a uniform random distribution on the interval [50%, 100%], and the required SoC at the destination is drawn from a uniform random distribution on the interval [0%, 40%].

All the trucks in the simulation have a useful battery capacity of $B_{cu} = 500$ kWh, a speed of $v = 75$ km/h and have an energy consumption of $\frac{\Delta E}{\Delta x} = 1.5$ kWh/km. To have good initial conditions the model simulates two consecutive days. The first simulated day starts with no trucks on the road and empty charging stations, and with the same prices for charging and truck flows as for the typical day. The second day therefore starts with some trucks already on the road and some using the charging stations. In the analysis only the results from the second day are used. So, each truck in the simulation has a starting position and a destination in either Helsingborg, Jönköping, Linköping, or Stockholm. Each truck enters the highway at a certain time, with a certain SoC and an individual requirement on the SoC at the destination. However, none of the trucks enter the highway with less than 50% SoC and no truck must have more than 40% SoC when they exit the highway.

In reality, there are laws that regulate how long the drivers are allowed to drive. For example, the drivers must take a break after at least 4.5 hours of driving. This constraint is not explicitly used in the simulations, but due to their battery size the trucks cannot run for more than 4.5 hours at 75 km/h without charging, inferring this constraint is fulfilled anyway. Also, the fact that the driver must take breaks under some conditions might affect where and when they choose to charge, but the total amount of charging will not be affected.

There are charging stations along the road, and the number of charging stations, their position, and the number of chargers at each station varies from simulation to simulation. The price for charging depends on the station and the time of day but has been set to the same value in almost all simulations. In all simulations there will be at least three charging stations along the road and these three will be uniformly distributed along the highway. All the chargers are assumed to have a power $P = 700$ kW. Further, it is assumed that this power can be used for all trucks regardless of their battery SoC. This implies that a truck will always be able to fill their whole useful capacity in 43 minutes if needed.

To perform the simulations the charging behaviour of the trucks must be decided. This behaviour is described below. In the simulation each truck, i.e., each agent, will act according to the following rules:

1. The trucks only charge when they need it to complete their mission, and only what is needed to have the required SoC at their destination.
2. The trucks will not charge more times than necessary. This will, together with the assumptions that were presented earlier, imply that none of the trucks will charge more than twice. The assumptions also prevent a truck from reaching zero SoC before it reaches a charging station.
3. If a truck needs to charge twice, it will charge full, the first time it charges.
4. A truck arriving to charge at a charging station will continue to the next charging station if there are too many trucks queuing and if it has the possibility to reach the next charging station. The queue is judged to be too long if the fraction of queuing trucks divided by the stations total number of chargers is greater than the parameter $r_{queuing}$.
5. Trucks that have possibility to select between stations while following the rules above, will choose to charge at the lowest price. Trucks that are charging twice minimize the price for the first charge. When the prices between two compared stations are equal the truck selects the nearest of those stations.

The truck flow and the charging rules make it possible to create an agent-based model where each truck is one agent. The aim is to select the number of chargers in the system such that the utilisation is high while the queues are short. The main results and conclusions from the simulations are listed below.

• A future system of battery electric trucks and public fast chargers along the highway between Helsingborg and Stockholm seems to function very well. Due to the relatively uniform traffic flow of the trucks the simulations point to a system with low prices on public fast charging, profitable charging stations, high charger utilization and few problems with queues at the charging stations. The system will also be robust towards an increase in the traffic flow or an unusual peak in the traffic flow.

• The simulations indicate that a system with a fixed number of chargers resists queues better if there are a few charging stations with many chargers rather than many charging stations with few chargers.

This is clear from a simulation where 105 chargers are distributed over first 3 sites and then over 6 sites. This effect could be explained by the risk of ending up in a queue where all the charging trucks just have started charging is larger for a small station then a big one but also due to that if you, for example, have a station with ten chargers and ten charging trucks there is no queue but if this ten chargers are distributed in space there could be a queue at one station and a free charger at another if not the trucks are distributed perfectly.

- It is estimated that there is a need for 140 chargers with the power of 900 kW along the highway between Helsingborg and Stockholm for a full electrification of the current long-haul truck fleet. The 900 kW chargers will be able to deliver the average power of 700 kW as the ones in the simulations. However, this low number of chargers seems only possible when the chargers are collected in a few locations with many chargers at each location. If the chargers should be placed according to EU Alternative Fuel Infrastructure Regulation (AFIR) this solution is not allowed. Therefore, the number of chargers will be higher later in this thesis.

- The system charger utilization factor is estimated to be 30% which should be considered as a high value for a system with small problems with queuing. In reality, the charger utilisation will be lower, but still high, if one follows the AFIR rules. A value for that case will be presented later in this thesis.

- Simulation shows that it may be hard to use time-varying pricing to improve queuing conditions on a system level, since varying prices seem to reduce the queuing in one station by moving the queue to another station.

- The truck's willingness to change charging stations to avoid queues is an important property and leads to less queuing at the system level.

4.7 Competition Between Charge Point Operators at the Same Site

From above, it seems possible to archive high utilisation of public chargers along the Swedish highway E4 which enables low prices on fast charging. However, so far, the total number of chargers has been tuned manually with the aim of low queuing problems, and the price is just assumed to be low due to low cost per kWh for the charge point operator in this system. In the future, one will likely see competing charge point operators on a free market like today's gas stations. This insight raises some questions such as: Will commercial charge point operators build enough chargers to meet the peak demand? Will the prices be reasonable? Will the prices vary over time?

To investigate this an agent-based model with two competing charge point operators at the same site was constructed. The main idea is to now treat both the charging trucks, and the charge point operators as agents. The trucks select charge point operator to minimise their cost while potential queuing time is included in their charging-decision, while the CPOs (Charge Point Operators) adjust their prices and number of chargers to improve their profit. The changes in price can only be made in small steps. The same day, which will be referred to as *the typical day* will be simulated over and over again and in-between these iterations one of the two CPOs can adjust their prices and number of chargers. If the profit for the CPO that made changes is improved the CPO will change to the new setup of prices and number of chargers, otherwise it will return to the previous one. After sufficiently many iterations of competition one reaches a so called *quasi-steady state* when one only has small fluctuations in prices and queues. This means that one can study prices and queues in the case when the market has reached an equilibrium point. Notice that this thesis only studies a potential quasi-steady state that the market can end up in, not the time development of prices and queues during the phase before the quasi-steady state. For the complete algorithm description, see Section 3 in Paper D.

The site under investigation is meant to represent Ödeshög, located midway between Helsingborg and Stockholm (see Figure 4.9), at full electrification of the truck fleet. Ödeshög was chosen since it likely will have a high demand for public fast charging of long-haul trucks. Also, the driving distance from both Helsingborg and Stockholm suits the mandatory break, and it already has large truck stops. It is assumed that 499 trucks will charge 525 kWh each during the simulated day and the variation of the charging demand over that day is constructed to reflect the truck flow from data [70]. The flow of charging trucks that arrives at the site is shown in Figure 4.12 and is meant to represent a typical day at Ödeshög at full electrification.

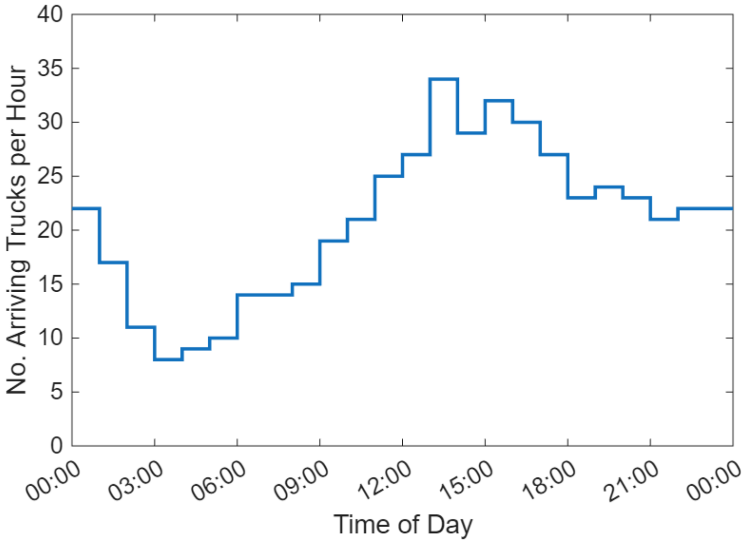


Figure 4.12: Total number of arriving trucks per hour that want to charge at one of the two stations as a function of time.

As mentioned above the CPOs want to improve their profit by adjusting the prices and number of chargers. The CPOs charging price paid by the trucks can vary each hour. In this thesis, “each hour” corresponds to the time intervals 00:00–01:00, 01:00–02:00, and so on. The price for electricity that the CPO pays is assumed to be constant and is set to the same value as previously ($C_e = 0.08$ EUR/kWh). The trucks that arrive at the stations charge at the price when they arrive, regardless of any price changes during charging and potential queuing. The profit for each CPO on the simulated day is calculated as

$$I = \int_0^T \left(C_{epub}^{mean}(t) - C_e\right) \cdot P \cdot N(t)\, dt - C_{ch} \cdot r_p \cdot P \cdot N_{tot}, \tag{4.34}$$

where the parameters and variables in the above equation are defined in Table 4.6 except for the factor $r_p = \frac{9}{7}$, which is a factor that compensates for the fact that the charger does not run on full power all the time. The assumed value of $r_p = \frac{9}{7}$ corresponds to a charger of 900 kW, which is expected to deliver 700 kW on average during a charging session. To summarise the above equation, the integral term represents the daily income paid by the users minus the cost of the bought electricity, while the second term represents the daily cost for the chargers and their grid connection.

Table 4.6: Definition of parameters and variables.

Notation	**Explanation**
$[0, T]$	Time interval over the analysed typical day
$C_{epub}^{mean}(t)$	Mean price per kWh paid by the users at time t
$C_e = 0.08$ €/kWh	Purchase price for electricity from the grid
$P = 700$ kW	Average power of a charger when it is in use
$N(t)$	Number of chargers which are used at time t for a CPO
$C_{ch} = 0.32$ €/kW/day	Total cost per day for a charger per kW of its rated power
N_{tot}	Total number of chargers of a CPO

When the model is run, one obtains results like the ones shown in Figure 4.13 and 4.14. The left-hand side of Figure 4.13 shows typical results of the prices during the typical day in quasi-steady state. One may see that the price has large variations during the day. During large parts of the day the price is just slightly over the price of electricity with the rush hours as exception. During the rush hours the price is clearly higher, but still reasonable (around 0.4 €/kWh). In Paper D, Subsection 5.1, it is shown by analytic calculations on a simplified case that it is reasonable with low prices as soon as the supply of charging is a bit larger than the demand. The calculations also show that it seems to be more profitable to let the price vary with the demand rather than have a fixed price. The right-hand side of Figure 4.13 shows how the prices develop over the iterations. One notices that the lowest price during the day is stable while there are small fluctuations in the peak price. The left-hand side of Figure 4.14 show the queuing conditions during the same day as the diagram showing the price variations (in Figure 4.13). One notices that there are almost no queues during the day with the rush hours as exception, but even during these hours the queues are small, around 0.1 queueing trucks per charger corresponding to around 2 minutes of queueing time. The right-hand part of the figure shows how the queues develop during the whole simulation. It shows that there are no severe queues in the quasi-steady state.

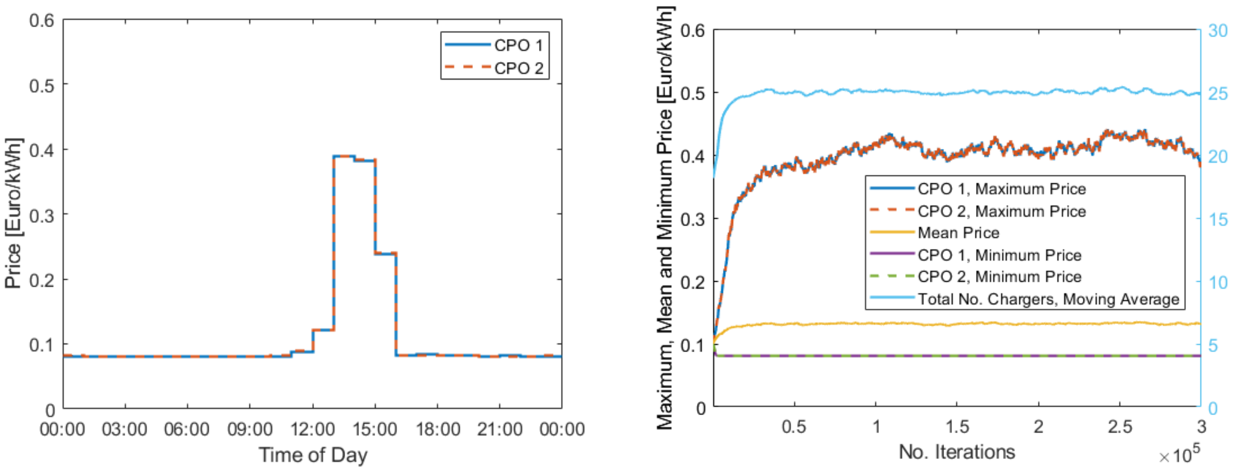


Figure 4.13: The left-hand part of the figure shows the price over the day for arriving trucks for the last iteration. The right-hand part of the figure shows the maximum, mean, and lowest price over the iterations shown on the left y-axis and moving average, over 10^4 iterations, of the total number of chargers in the system on the right y-axis.

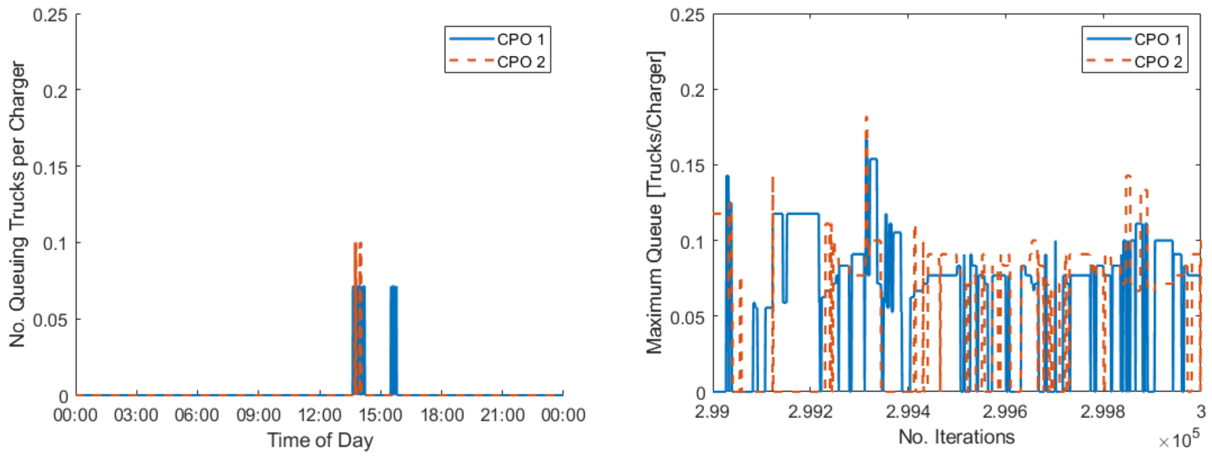


Figure 4.14: The left-hand part of the figure shows the length of the queue that a truck arriving at different times of the day will experience for the last iteration. The right-hand part of the figure shows the maximum queue over the day over the iterations.

So far, the prices shown in the result are based on the assumption that the traffic flow is exactly the same each day since the typical day has been simulated several times. In the real world, there are variations in charging needs between the days and likely less charging demand on weekends. Therefore, the charger utilisation has been adjusted to be representative of non-modelled flow variations. When the total number of chargers has been increased to handle non-modelled peaks in the charging demand, the lower charging need on weekends has been taken into account, and the delivered average charging power has been set lower than the maximum charger power, one obtains a utilisation as high as 31%. Under the assumption that the CPOs will have the same profit as in the original simulation, new charging prices can be found. The adjusted peak charging price is 0.5 €/kWh and the average price is 0.15 €/kWh while the price in calm hours still is expected to be low, around 0.1 €/kWh. These prices seem reasonable or even low and is not obtained at the expense of the profitability of the CPOs. This investigation indicates that the CPOs, if the truck companies accept these prices, will build enough chargers to avoid severe queues. The reason for this promising result is the high charger utilisation which is possible since the flow of trucks is quite even during the day. The result also indicates that time-varying prices will outcompete fixed ones and that the free market can provide a system of chargers with high utilisation, profitable CPOs, low queuing problems, and reasonable prices for public fast charging in the long run, only due to competition and profit interests.

However, the investigation so far has only taken one site into consideration. In reality there will be competition also with charging stations located in other places. Since the trucks need time to drive along the road, the rush hours will be at different hours at different sites along the road, as can be seen in Figure 4.11. As the last development of the agent-based model done in this thesis, competition between geographically spread charge point operators is investigated and discussed in the next subsection.

4.8 Competition Between Geographically Spread Charge Point Operators

This section describes the last development of the agent-based model done in this thesis. Roughly, one may say that the two previous models have been combined into one, but with important differences. The full algorithm description can be found in Paper E, but the following summary is a less detailed overview. The trucks charging need are very similar to the one used in the first model designed to investigate queues and charger utilisation along the road between Helsingborg and Stockholm. This charging need is again meant to represent a typical day. Along the road there are several charging sites, with equal distance between each site. At each site there are two CPOs. Figure 4.15 illustrates this for a case with three sites.

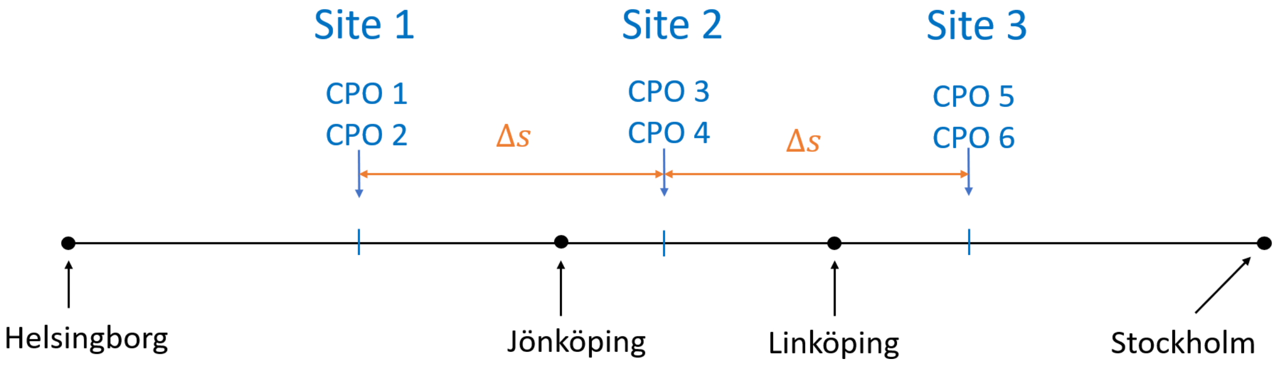


Figure 4.15: Illustration of the location for the CPOs with three charging sites

As in the previous model, the typical day is simulated repeatedly and one of the CPOs at each site updates the number of chargers and prices in between each iteration. This is done until the simulation results reach a quasi-steady state where the results are studied. This time the CPOs, under some circumstances, have the possibility to change the price in larger steps than in the previous model, resulting in a broader and more realistic search space for the CPOs. The aim of this agent based model is to estimate typical prices and queues in a future public fast charging market for trucks. Therefore, results like the mean charging price and mean queueing time for the whole system are of special interest.

In the simulations, the trucks are either extra sensitive to price *or* queues when they select charging site. All trucks have the same charging behaviour in the same simulation. When the trucks are sensitive to the price, they aim to charge at the site with the lowest price and may drive past a site with only slightly higher price but no queue. In the case when the trucks are sensitive to queues, they may charge at a site with high prices because the queue is short or non-existent, even if there are sites with clearly lower prices further down the road. The two different behaviours only affect the choice of site. Once the site has been selected, a truck always selects the CPO associated with the lowest cost, including the potential cost for queuing. These two behaviours could be seen as extreme behaviours which possibly constitutes boundaries for the future queues and prices.

Below, the results from three different modelled cases are shown. In Case 1 the trucks have price-sensitive behaviour and there are ten charging sites with 60 km between each site. Case 2 is the same simulation with the difference that the trucks have queue-sensitive behaviour. In Case 3 the trucks are sensitive to price but there are only three charging sites with 138 km between the sites. Notice that Case 3 in this thesis corresponds to Case 4 in Paper E. The cases are summarised in Table 4.7.

Table 4.7: Set up for different simulated cases. Notice that Case 3 in this thesis corresponds to Case 4 in Paper E.

Case	Behaviour	Distance between stations (km)
1	Price sensitive	60
2	Queue sensitive	60
3	Price sensitive	138

Results from Case 1: Price-Sensitive Trucks

Results from the price-sensitive trucks with ten charging sites are shown below. Figure 4.16 shows how the minimum and maximum price over the day develops over the iterations for some of the CPOs. The other CPOs have similar prices. As previously, the CPOs could set different prices each hour. Notice that there is only a small difference in price between the lowest and highest price, thus the price is quite even during the day. Also notice that the highest price is quite low, significantly below 0.2 EUR/kWh. Figure 4.17 shows how the price varies over the day for CPO 5 and 6 for the last iteration. Figure 4.18 shows how the system mean price and the total number of chargers in the system develop over the iterations. The system mean price is calculated by dividing the total charging cost for all the trucks by the total amount of energy delivered to all trucks during the typical day. As seen from Figure 4.18, the searched quasi-steady state seems to have been reached in the end of the simulation. Therefore, the following result is obtained by averaging over the last $1.5 \cdot 10^4$ iterations. The mean price in the system is found to be 0.113 EUR/kWh, the total number of chargers in the system is 89, the chargers are used on average 68 % of the time, the total profit for the CPOs is found to be 7,770 EUR/day, the mean queuing time per charge is 8.2 minutes, and the worst total queuing time for one truck for the typical day was 102 minutes (the truck might charge twice).

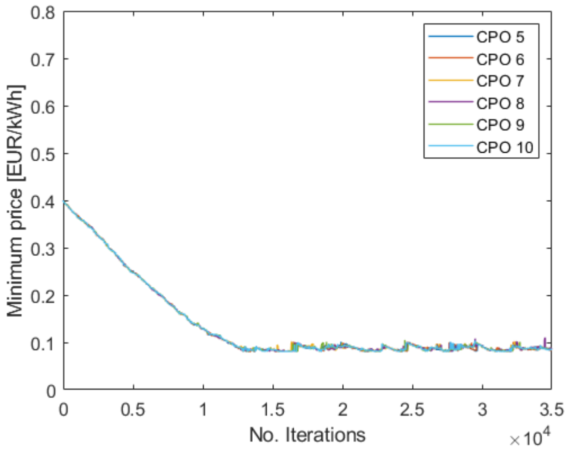
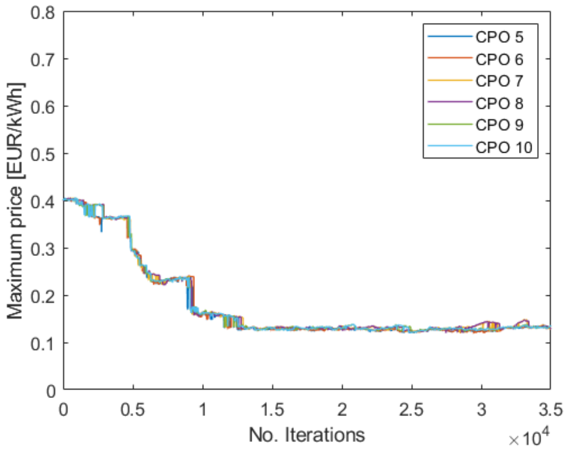


Figure 4.16: How the price develops over the iterations for some of the CPOs. The left-hand part of the figure shows the minimum price over the day, and the right-hand side shows maximum price over the day.



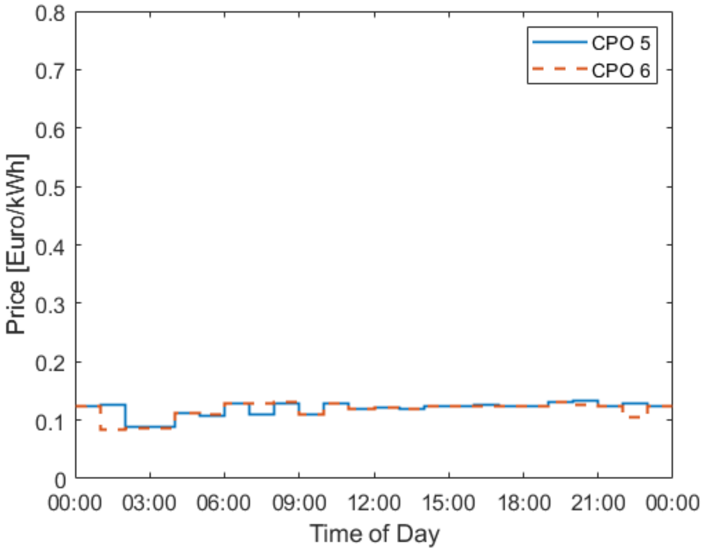


Figure 4.17: The price over the day for CPO 5 and 6 for the last iteration.

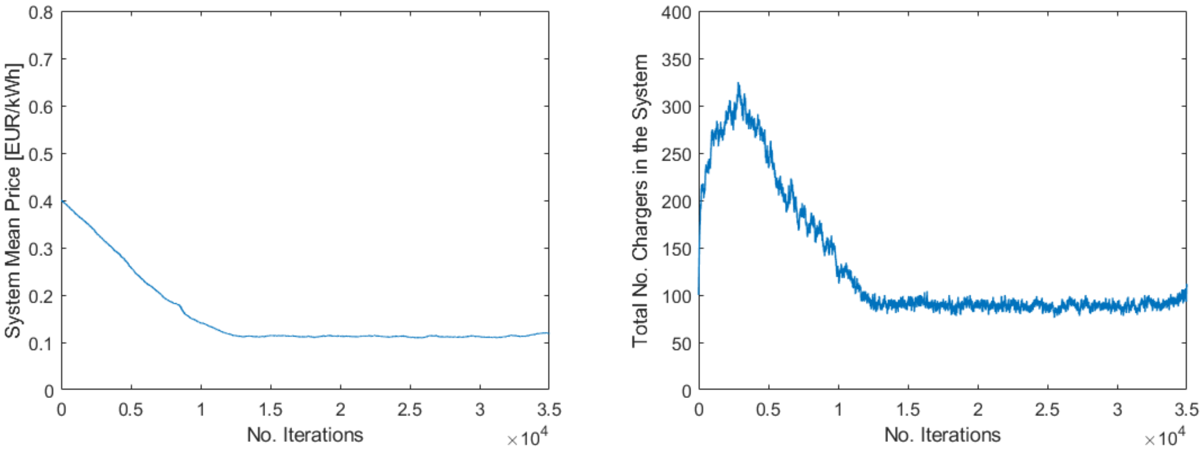


Figure 4.18: The left-hand part of the figure shows how the system mean price develops over the iterations while the right-hand side shows how the total numbers of chargers develop over the iterations.

Results from Case 2: Queue-Sensitive Trucks

Results from the queuing-sensitive trucks with ten charging sites are shown below. Figure 4.19 shows how the minimum and maximum prices during the day develop over the iterations for some of the CPOs. The other CPOs have similar prices. In this case, there is often a significant difference between the lowest and highest price. The right-hand part of Figure 4.19 shows that the highest price for CPO 17 and 18 tends to be very high and around 0.7 EUR/kWh for the last iteration. However, the price is only that high for one hour while the rest of the hours have significantly lower prices, see the left-hand side of Figure 4.20 which shows the price over the day for the last iteration. The right-hand part of Figure 4.20 shows the number of queuing trucks per charger over the day for the last iteration for CPO 17 and 18. Although the queue-conditions could rapidly change over the iterations at a specific site, the figure shows that there is a small lack of chargers during the hour when the price is high. The queue consists of only one truck. Since the price is equal between the two CPOs during this hour, the arriving truck that could not find a charger has selected CPO 18 due to it having more chargers than CPO 17. CPO 18 has 6 chargers in this iteration, and CPO 17 only 4. Thus, a truck will choose CPO 18 as that means standing in a queue with fewer queuing trucks per charger. The figure shows that the queue is at lunchtime. However, this is not true in general. At other sites, the rush hours can be during other times. As seen from the figure, the queuing problems are small for this site and specific iteration, something that is also true for all the other sites during iterations in the quasi-steady state. Figure 4.21 shows how the system mean price and the total number of chargers in the system develop over the iterations. As seen in Figure 4.21, the searched quasi-steady state seems to have been reached in the end of the simulation. Therefore, the following result is obtained by averaging over the last $1 \cdot 10^4$ iterations. The mean price in the system is found to be 0.225 EUR/kWh, the total number of chargers in the system is 175, the time-utilisation for the chargers in the system is found to be 35% , the total profit for the CPOs is found to be 97,100 EUR/day, the mean queuing time per charge is 0.1 minutes (6 seconds) and the worst total queuing time for one truck for the typical day is 21 minutes (the truck might charge twice).

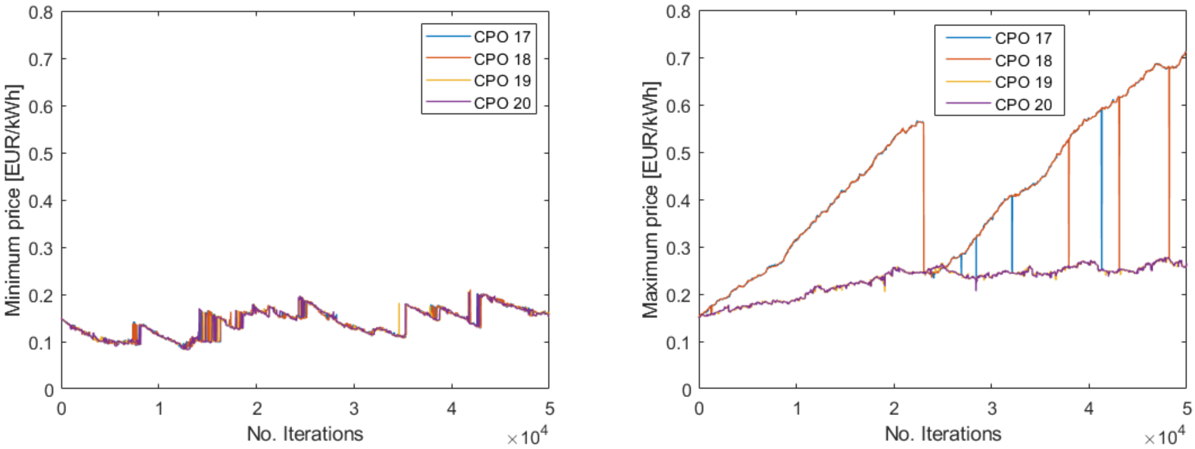


Figure 4.19: How the price develops over the iterations for some of the CPOs. The left-hand part of the figure shows the minimum price over the day, and the right-hand side shows maximum price over the day.

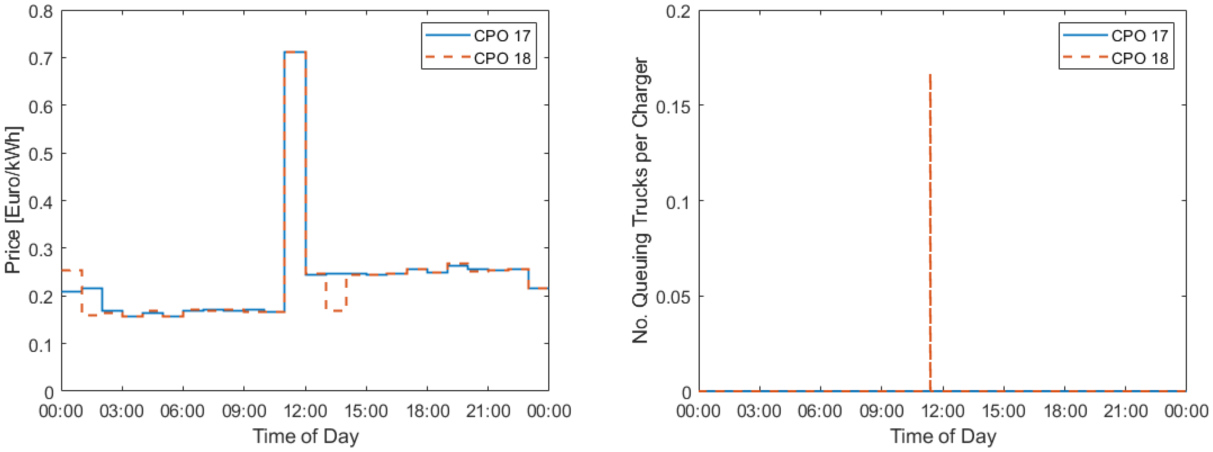


Figure 4.20: Prices and queues during the day for the last iteration for CPO 17 and CPO 18. The left-hand part of the figure shows the price, and the right-hand side shows the queuing condition.

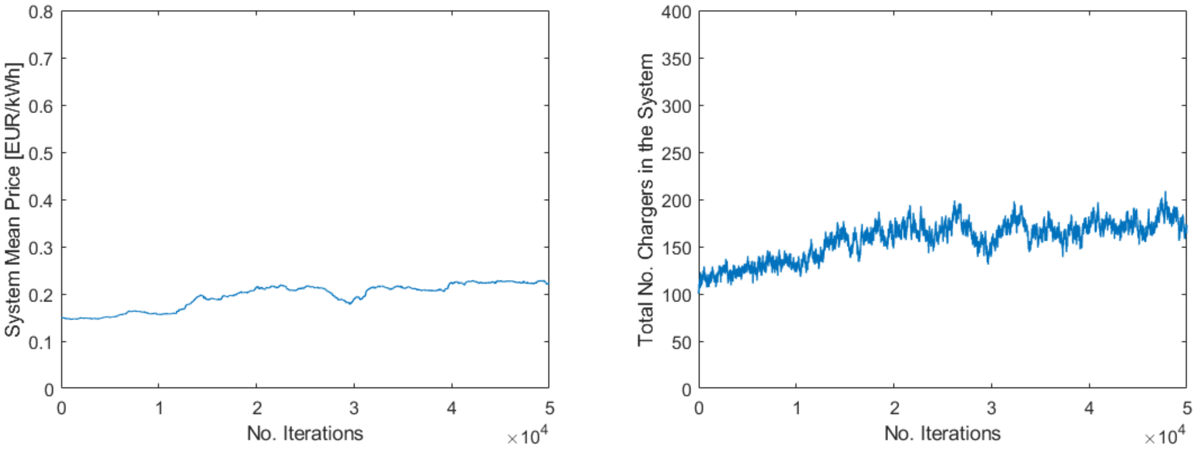


Figure 4.21: The left-hand part of the figure shows how the system mean price develops over the iterations while the right-hand side shows how the total numbers of chargers develop over the iterations.

Results from Case 3: Three Charging Sites Only

Results from the price-sensitive trucks with only three charging sites are shown below. Figure 4.22 shows how the minimum and maximum prices over the day develop over the iterations for all CPOs. The difference between the lowest and highest price is, as in Case 1, small. Thus, the price is quite even during the day, and the highest price is quite low. Figure 4.23 shows how the system mean price and the total number of chargers in the system develop over the iterations. As seen from Figure 4.23 the searched quasi steady state seems to be reached early in the simulation. From the right-hand side of Figure 4.22 it can be seen that the maximum price for the site with CPO 5 and CPO 6 increases strongly during three iteration-periods, but since the mean price is not affected much one may suspect that the price is high only for one or a few hours during the day. The following results are obtained by averaging over the last $1.5{\cdot}10^4$ iterations. The mean price in the system is found to be 0.135 EUR/kWh, the total number of chargers in the system is 95, the time-utilisation for the chargers in the system is found to be 64%, the total profit for the CPOs is found to be 28,600 EUR/day, the mean queuing time per charge is 1.7 min and the worst total queuing time for one truck for the typical day is 32 min.

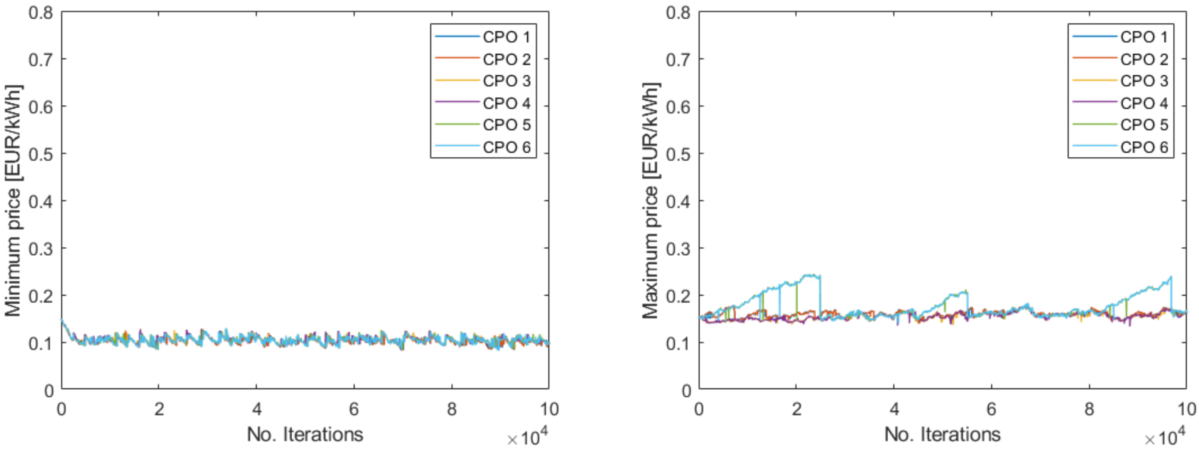


Figure 4.22: How the price develops over the iterations for the CPOs. The left-hand part of the figure shows the minimum price over the day, and the right-hand side shows maximum price over the day.

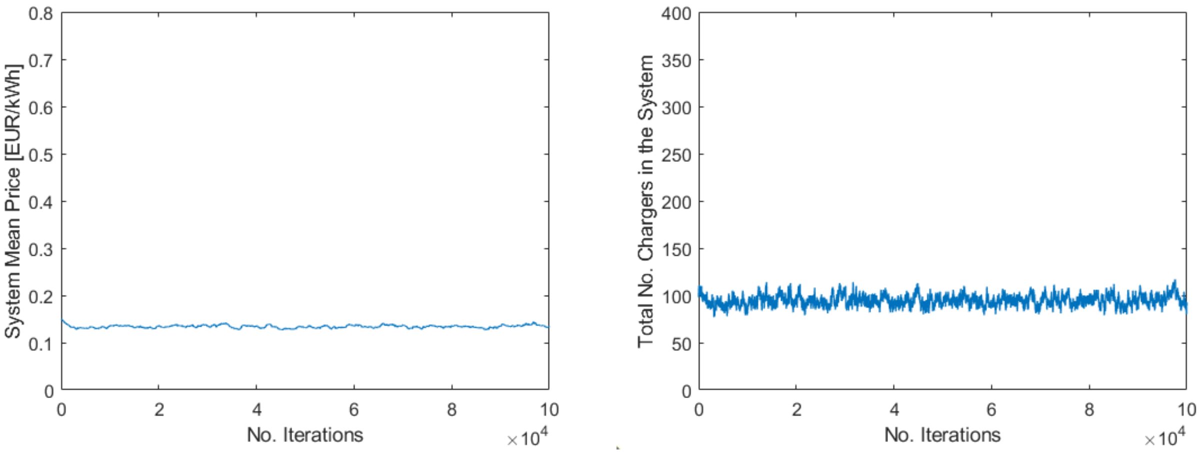


Figure 4.23: The left-hand part of the figure shows how the system mean price develops over the iterations while the right-hand side shows how the total numbers of chargers develop over the iterations.

Summary and Discussion of the Results

Previously, results from three cases of competing CPOs and charging trucks have been presented. Below the results are summarized and discussed. An overview of the results is presented in Table 4.8.

Table 4.8: Summarised results.

Case	Mean price (EUR/kWh)	Mean queueing time (min)	Total number of chargers (-)	Time utilisation of chargers (-)
1	0.113	8.2	89	68%
2	0.225	0.1	175	35%
3	0.135	1.7	95	64%

Case 1 shows a really low price for public fast charging but at the expense of some severe queues. The simulated truck behaviour could be seen as extreme since a truck can bypass a site with free chargers just to have slightly lower price at another station but with risk of long queues. In reality drivers will likely not behave in this way, and this mean price can be seen as a lower limit. Since the prices are low it is reasonable to sometimes have queues since the prices are not high enough to make it profitable for the CPOs to build chargers to meet the peak demand. Also, a typical day is simulated but without respect to the variation in the traffic flow over the year. To have a system that is robust towards queues it is necessary to have more chargers than for the typical day. But, since it does not seem profitable for the CPOs to build chargers for the peak demand of the typical day, they will probably not build even more chargers to meet an even higher peak demand some days. This means that the queueing conditions will be even worse some of the days but also better some days when the traffic flow is lower. In a system like this a charger booking system could be a part of the solution. A booking system may help better distribute the trucks over the existing chargers and could in the best case broaden the demand-peak, which could lead less queuing problems. However, it will not directly create *more* chargers which is required if the number of chargers is too low. In Case 1, the price is quite even over the day, and the price is rarely at the lowest level. This result contradicts the previous result from the model with only one site. A natural conclusion is that geographically spread CPOs give rise to a more even price structure over the day. But this is only partially true, and the difference could also be explained by the new update rules for the CPOs which make it possible for them to change prices in greater leaps than was possible in the previous model.

In Case 2, the trucks are queue sensitive but not as price sensitive as in Case 1. In the extreme case, the trucks could stop at a site with very high prices just because the queues are short or non-existent. This behaviour gives rise to a system with many chargers and almost no queues but with significantly higher prices compared to Case 1. In Case 2, the price is quite even over the day if some hours are excluded, but for some hours the price could be really high. This is similar results as from the previous model in which only one site was investigated. Now, when the trucks stop and charge if the queues are sufficiently small regardless of price, the variation in charging demand at each site is likely lower between the iterations compared to Case 1. In Case 1 all trucks aim for the site with the lowest price for each iteration which pushes the price to a more even level over the day. The author interprets the above as the geographical spreading of the CPOs, in Case 2, having less impact, and the price picture over the day is more like the results from the previous model. This indicates that a system where trucks select between sites that are geographically spread will generate more even price pictures over the day than if trucks always charge at the same site. However, the price is not at the lowest level in large parts of the day as earlier. The reason for this is that the CPOs now can change the price in larger leaps than before. Previously the price where at the lowest level as soon as the charging demand is a bit lower than the supply. This can be explained by the fact that the CPO that has a price slightly less than the competitor, will get many more customers. A price increase with just a small step is not enough to earn more money from the higher price than what is lost from having fewer customers. When the CPOs can change the price in greater leaps, the CPOs can increase the price and still earn more money despite the loss of customers. Now, consider the left-hand side of Figure 4.19. One notices the same behaviour as in the previous model, the minimum price decreases over the iterations but now, at some point the price is increased with a large step and then falls again and so on. In reality, the CPOs will be able to increase the price more than just a small step and one may therefore see the new added rules for the price as an improvement of the behaviour of the CPOs.

In Case 3 the trucks are sensitive to price and there are three charging sites only. Due to the large distance between the sites, fewer trucks can select more than one site so one may guess that it is not as important if the trucks are sensitive to price or queues. This case leads to a system with low prices and small queueing problems! The mean price is a bit higher than in Case 1 and there are some more chargers as well. However, this is not the main reason for the lower queuing problem compared to Case 1. It could rather be explained by the result from the first agent-based model presented in this thesis which declares that fewer large charging sites better resist queues than many small ones (provided that the total number of chargers are the same). By the EU Alternative Fuel Infrastructure Regulation, the distance between sites should be no more than 60 km along larger roads, as in Cases 1 and 2. There could be benefits with more dense charging sites, such as trucks can avoid detours for charging, but from this result there also seem to be drawbacks. Thus, the results from Case 3 indicate that the minimum distance law could have some negative effects.

Further Analyses of the System with Queue-Sensitive Trucks (Case 2)

The author thinks that the results from Case 2 when the trucks are queue sensitive are of special interest since they can give an upper bound for the mean price for roads with similar conditions as the studied one. Therefore, Case 2 will now be further investigated, starting with corrections of the mean price and charger utilisation for non-modelled flow variations over the year. In the case of queue sensitive trucks, the prices for fast charging get sufficiently high so the CPOs meet the peak demand for charging. This makes it likely that they, in reality, would build even more chargers so the system can resist queues even at peak demands higher than the typical day, since the trucks are willing to pay to avoid queues. The other studied cases resulted in lower mean price, therefore, this value can be seen as an estimate of an upper bound for the mean prices for roads with similar conditions as the studied road. The typical day represents a weekday, but there will likely be fewer trucks on the road at weekends and the flow variations over the year will be more uneven than the flow of the typical day. Therefore, there is probably a need for more chargers than were found in the simulation and the CPOs will lose some income due to lower charging demand on weekends. It is assumed that the CPOs will increase their prices to compensate for this, and now the price and charger utilisation will be adjusted to account for the above. This is done in the same way as in Paper C where it is assumed that the charging need over the week is reduced by $\frac{1}{7}$ because of lower charging demand on weekends.

The number of chargers in the system is increased by 33% to be able to handle increased traffic and unexpected peaks in the charging demand over the year. The charging need for the typical day, E_{tot}, is $1 \cdot 10^6$ kWh. The mean price in Case 2 was 0.225 EUR/kWh, so the reduced profit due to weekends can be calculated as:

$$\begin{aligned}\text{reduced profit due to weekends} &= \frac{1}{7} \cdot E_{tot} \cdot (0.225 \text{ EUR/kWh} - C_e) \\ &= \frac{1}{7} \cdot 1{,}000{,}000 \text{ kWh/day} \cdot 0.145 \text{ EUR/kWh} \\ &= 21{,}000 \text{ EUR/day}.\end{aligned} \tag{4.35}$$

Further, the number of chargers in Case 2 was 175, so there is a need for $175 \cdot 0.33 = 58$ more 900 kW chargers. Since $C_{ch} = 0.32$ EUR/kW, the extra cost for chargers is found by:

$$\text{cost for extra chargers} = 58 \cdot 900 \text{ kW} \cdot 0.32 \text{ EUR/kW/day} = 17{,}000 \text{ EUR/day}. \tag{4.36}$$

The two equations above give the total extra income needed to compensate for the non-modelled flow variations over the year

$$\begin{aligned}\text{total extra income needed} &= \text{reduced income due to weekends} + \text{cost for extra chargers} \\ &= 21{,}000 \text{ EUR/day} + 17{,}000 \text{ EUR/day} \\ &= 38{,}000 \text{ EUR/day}.\end{aligned} \tag{4.37}$$

It is assumed that the profit will be the same with less demand and the extra chargers. Therefore, the charging price has to be corrected. Exactly how this extra cost will be distributed over the day will not be discussed in this thesis, but the new mean price can now be calculated:

$$\text{Mean price after adjustment} = 0.225 \text{ EUR/kWh} + \frac{38{,}000 \text{ EUR/day}}{1 \cdot 10^6 \text{ kWh/day} \cdot \frac{6}{7}} = 0.269 \text{ EUR/kWh}, \tag{4.38}$$

where the factor $\frac{6}{7}$ corresponds to the reduced charging need on weekends. The extra 58 chargers make it likely that there will be no queues most of the days, and only small queues for days with increased charging demand or when there are unexpected peaks in the traffic flow (maybe except for some days with extreme charging demand). Even the charger utilisation should be corrected. The time-charger utilisation was found to be 35% for Case 2. When compensating for the extra chargers, weekends and that a 900 kW charger on average delivers 700 kW one obtains the adjusted *energy*-utilisation:

$$\text{Energy-utilisation after adjustment} = 35\%/1.33 \cdot \frac{6}{7} \cdot \frac{700}{900} = 18\%, \tag{4.39}$$

which is less than what was found previously (30%) but still fairly good. The reason for the lower value in this study, found from Case 2, is that the chargers are dispersed over more charging sites due to the EU Alternative Fuel Infrastructure Regulation. In reality, queues or higher prices at rush hours will likely make some haulage companies reschedule their trips, which have not been included in here. However, such behaviour would lead to higher utilisation of the chargers and likely lower average charging prices. The above calculations also show that there is a need for 233 chargers, each with 900 kW power, if all the long-haul trucks that drive along the studied highway are electrified. This is more than what was found previously (140 chargers) for the same reason as above. It is important to mention that the estimate of the number of chargers is rough and it is sensitive to the trucks charging strategy which likely will depend on for example the charging price, the battery price and the pay-load capacity.

A mean price of 0.27 €/kWh with small queueing problems and robustness towards unexpected peaks in the traffic flow seems promising. It is important to emphasis that these prices are not achieved at the expense of low profitability of the CPOs. In Paper E the return on investment is found to be 21%. This should be interpreted as the invested capital returning an interest of 21% every year which shows good profit potential for the CPOs. The corresponding value for Case 1 is clearly lower (7%). This shows that the trucks' behaviour, as a collective, can have great influence on the profitability of the CPOs. The results from this model also indicate that the haulage company's behaviour clearly can have impact on the price level and queueing problems in the system. If they want low prices, they get low prices but to the cost of higher risk for severe queues, if they want a system with small queueing problems it seems possible with higher, but still reasonable, prices.

5 Results and Conclusions

During the work presented above several assumptions and simplifications have been made, including the selected values of the cost parameters. This was necessary to understand the mechanisms that are important for cost effective battery electric trucks and chargers. Of course, more details could be included, not least in the agent-based models in which a complex system has been studied with fairly simple models. However, there is certainly no guarantee that more complicated models would have given more accurate results or a better understanding of the future system of battery electric trucks and their chargers. Despite the complexity of the problem studied, this thesis has produced some interesting results and conclusions which are listed below which together add significantly to understanding electric trucks from a system perspective.

1. The battery electric trucks seem to become cost competitive compared to the cost of today's commercial diesel trucks in many cases.

2. High utilisation of the batteries and chargers is essential for cost effective battery electric trucks. High battery utilisation is easiest achieved if the truck has similar transport task each day and high fast charger utilisation is facilitated by a fairly even flow of charging trucks during the day, while night chargers achieve high utilization if they are used many hours per night.

3. A battery electric truck must do approximately 1400 trips or more during its service life to be cost competitive to the diesel option, otherwise the battery and depot charger utilization cannot become high enough.

4. A system with few charging stations seem to resist queues better than a system with many, if the total number of chargers is the same.

5. The EU Alternative Fuel Infrastructure Regulation (AFIR) demands the distance between charging sites to be no more than 60 km along larger roads. Simulations show that this could have some negative effects since it could force more stations along a certain distance than necessary which results in many stations with fewer chargers, see the above conclusion in the list.

6. The truck's willingness to change charging stations to avoid queues is an important property and leads to less queuing at the system level.

7. Roads with similar traffic flow as the E4 highway between Helsingborg and Stockholm in Sweden seems to have good opportunities for a future public fast charging market for trucks. High charger utilisation, small queueing problem and fairly low prices should be possible due to a quite even flow of trucks over the day.

8. It has been estimated that for roads with similar traffic flow as the E4 highway between Helsingborg and Stockholm in Sweden a mean charging price for public fast charging of 0.27 €/kWh or lower should be possible, achieved with low queuing problems, resistant towards unexpected peaks in the traffic flow and with profitable charge point operators.

9. The price for public fast charging could also be significantly lower than the above value in the list, like 0.11 €/kWh, but in such system, it will not be profitable for the CPOs to build chargers

for the peak demand of charging, resulting in severe queues for some trucks. In this case the average queueing time per charge was found to be eight minutes.

10. The haulage companies, as a collective, can affect the future fast charging market to a great extent. If they reward low prices, they will probably get low prices to the risk of severe queues but if they accept higher prices there will likely be small queueing problems.
11. It has been estimated that for a full electrification of the truck fleet there is need for 233 fast chargers along the E4 highway between Helsingborg and Stockholm, each with a power of 900 kW and with a predicted energy-utilisation of 18%. It is important to mention that the estimate of the number of chargers is rough and is sensitive to the trucks charging strategy which likely will depend on, for example the charging price, the battery price and the needed pay-load capacity while the estimated value of the energy utilisation is more reliable.
12. A charge point operator that uses time varying prices will likely outcompete one that uses a fixed price over the day.
13. The system of battery electric trucks and their chargers have potential to be well functioning and cost effective at full electrification. It seems likely that the market on its own can provide a public fast charging market with low queueing problems, reasonable charging prices and profitable CPOs. Subsidies might be good for accelerating the transition from diesel trucks to electric ones but will likely not be necessary in the long run.

6 Future Research

This thesis contributes to better understanding how battery electric trucks for medium and long distances can be operated in a way which is cost effective, but there are still a lot of things that need to be discovered, improved, verified or questioned before we have the full picture. For example, in Paper B the potential cost for losing payload capacity due to a large battery is found to be high. This could have a large effects on the charging strategy for battery electric trucks. To understand if this potential extra cost is a widespread problem, information about how high payload the trucks carries should be desirable. To find and present this information in a clear, compact and convenient way could be a good contribution to the research filed of battery electric trucks. Loss of payload can then be added as one more term in the cost function which takes the potential cost for losing payload capacity into account in analyses similar to the ones done in Paper A. This term should then depend on the battery capacity and the weight of the goods that the truck is carrying.

Further, when electric trucks are more mature, one should be able to find more up-to-date values on the cost parameters in analyses similar to the one performed in Paper A and B and these values should then be analysed in more detail than was done in this thesis. Also, an extensive sensitivity analysis should be performed since important conclusions are based on uncertain values of the cost parameters.

Regarding the agent-based models it would be interesting to modify the update rules for the CPOs pricing and number of chargers or even discover the opportunity to find profitable prices and number of chargers with another method than agent-based simulation. A memory for the trucks and CPOs might be used. For example, a truck that encounters a severe queue at a certain station might avoid that station in the future. Maybe some methods using artificial intelligence could be successful? However, the author of this thesis suspects that even simpler methods than used in this work can also be used to get good estimates of, for example the charging price. Can one just use the traffic data and size the number of chargers to the peak somehow? Further, one may assume hard competition between the CPOs which limits the profit for the CPOs which results in the mean price for public fast charging. Different methods, both simpler and more advanced, should be used to either modify or confirm the results from this thesis.

Finally, and in all humility, I think that the literature and this thesis strongly indicate that battery electric trucks are ready to replace the diesel truck, even if we do not know all details yet. Thus, one may ask the question; is more extensive research still needed to prove cost effectiveness and technical feasibility for the battery electric trucks? More research could be helpful in how to refine the system but maybe it is not so important to decide to start the transition.

7 Another Way of Reducing the Use of Fossil Fuel due to Transport

This chapter might be judged as misplaced since the content is beyond the scope of this thesis. However, I would like to express an idea that I think can help the world. I think it is a nice idea; some people might not like it. I think most of us will realise that it is true and many of us have likely already thought or talked about it themselves.

When an environmental problem is realised, we often seek a technical solution. Such as when we realise that we are dependent on fossil fuel which is a limited resource with harmful effects on the earth. Then we want a solution like replacing the diesel trucks with battery electric ones. I think that this solution can work well, but if we just have to replace a share of the diesel trucks and not all of them the problem becomes easier to solve. Should the rest still be running on diesel? No, they should be removed! If we all, together, try to be more frugal with the earth's resources, that is a part of the solutions, just like the battery electric trucks. This part of the solution requires no large batteries, advanced technology or agent-based models, only wisdom, long-term thinking and non-selfishness. Without unnecessary consumption, less trucks are needed and not the whole fleet needs to be replaced. There are a lot of difficult and important problems in the world, many of them with simple solutions, but still so hard to implement. Due to that, the short-term individual goal does not match the long-term collective goal or to that profit interests in companies do not always go hand in hand with what is best to mankind. However, the customers can change this through their decisions. We can make wise decisions even if it means that it leads to a bit less material prosperity. We have that choice, let us choose to do what is right.

8 Appendix

From "Naturvårdsverkets" [5] one knows that domestic transport accounts for a little less than one third of Sweden's total emissions of greenhouse gases. Also, one finds that heavy duty trucks (above 3.5 tone) are responsible for 2.8 million tone carbon dioxide equivalents of the 13.9 million tone carbon dioxide equivalents from domestic transport during year 2023. Since 0.3 is a little less than one third one gets

$$\text{the share of greenhouse gas from heavy duty trucks in Sweden} = 0.3 \cdot \frac{2.8}{13.9} \approx 6\%. \tag{8.1}$$

From the European Parliament [6] one knows that during year 2019 the transports in the European Union accounts for approximately one fourth of the total emissions of greenhouse gases of which 71.7% come from road transports. The heavy-duty trucks account for 27.1% of the greenhouse gas emissions from road transport. Thus, one obtains

$$\text{the share of greenhouse gas from heavy duty trucks in the European Union} = \frac{1}{4} \cdot 0.717 \cdot 0.271 \approx 5\%. \tag{8.2}$$

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