Investigating The Economical Impact of Smart Charging Strategies at a Fully Electric Truck Depot

Master's thesis in Sustainable Energy Systems [MPSES]

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Abstract

Reducing emissions from the transport industry is crucial if Sweden wants to reach the national goal of zero carbon emissions by 2045. A part of the solution is to shift from use of fossil fuel trucks to electric trucks. Which in turn will increase power demand from the truck depots and potentially lead to increased costs for depot owners and overloading the grid. The aim of this study is to investigate how the implementation of smart charging strategies can reduce cost and increase flexibility for a fully electric truck depot. This was done using historical data from a real life truck depot and a linear optimization model. The linear optimization model was used to represent three different charging scenarios, direct charging, smart charging and smart charging with a battery energy storage system. All scenarios were then run using two sets of electricity prices and the results from the two smart charging scenarios where then compared to the direct charging scenario. The results indicate that smart charging strategies have the potential of substantially reducing the total cost of electricity at the depot. It also shows that investments in increased flexibility by increasing the fuse size of the depot can be profitable if there is enough variation in the spot price of electricity. The results also indicated that investing in flexibility in the form of battery storage can reduce cost of buying electricity but will not be cost efficient when also considering the investment cost of the battery. Due to the many assumptions made in the study future research testing these assumptions will be needed in order to validate the findings of this study.

Keywords: Electrification, Smart charging, Electric trucks, Battery Electric Storage Systems,Truck Depots, Linear optimization

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Otto Olsson, Gothenburg, June 2025

List of Acronyms

Below is a list of acronyms that have been used throughout the thesis, listed in alphabetical order:

AC	Alternating current
BEV	Battery electric vehicles
BESS	Battery electric storage system
BET	Battery electric trucks
CCS	Combined charging system
CHAdeMO	Charge de move
CHV	Catenary hybrid vehicle
CRF	Capital recovery factor
DC	Direct current
FCEV	Fuel-cell electric vehicle
HAC	Hourly annualised cost
HDET	Heavy duty electric trucks
IEC	International electrotechnical committee
ISO	International organisation of standardisation
LNG	Liquid natural gas
LP	Linear programming
OBC	Onboard charging unit
PF	Power Factor
SAE	Society of automotive engineers
SOC	State of charge
SOH	State of health
TCO	Total cost of ownership
V2G	Vehicle to grid

Contents

List of Figures

List of Tables

1

Introduction

In this chapter the background of the thesis is presented in section 1.1 to provide context and relevance to the work. It also presents the aim of the thesis in section 1.2 and limitations made during the work in section 1.3.

1.1 Background

The total emission of CO_2 in Sweden was estimated to be a 44.3 million tonnes in 2023, where 13.8 million tonnes was emitted from the transport sector [1]. This represent approximately 31% of the total yearly emissions in Sweden. Reducing emissions from the transport sector is thus vital to reach the national goal of zero carbon emissions by 2045 [2]. How to reduce these emissions have long been a topic of research but a part of the solution is the electrification of the transport sector by replacing fossil fuels vehicles with battery electric vehicles (BEV) and investing in supporting infrastructure. The sales of battery electric cars in Sweden have steadily been increasing and predictions show that by 2030 battery electric cars can account for up to 50% of all newly registered cars [3],[4]. However, progress in the implementation of battery electric trucks have been slower, especially for heavy duty electric truck (HDET), due to historically low energy density and high cost of batteries [5]. In spite of this, the share of light electric trucks is predicted to increase rapidly in the upcoming years [3]. This is a result of many models of lighter electric trucks now being able to compete with their fossil fuel equivalent in terms of total cost of ownership and that a large portion of lighter electric trucks rely on overnight depot charging [6], which makes them less dependent on a well developed public charging infrastructure. However, there are still a number of barriers to overcome for truck owners and logistical providers operating these trucks to convert to a fully electric truck fleet. These barriers include the cost of purchasing new vehicles, cost of investing in the charging infrastructure at depots, grid capacity limitations, and general uncertainty and lack of trust to the new technology [7].

There is also concerns on how to handle the increased energy demand from the electrification of trucks. Especially for truck depots where some predictions estimate that the power demand of truck depots can increase up to ten times of their current levels [6]. This together with the general increase in electricity use in metropolitan areas, electrification of the other parts of the transport sector and of the industrial sector makes it necessary to invest more in electrical infrastructure to support the current rate of electrification [8]. Otherwise there is risk of the electrification of the transport sector being halted by lack of capacity in the grid [6]. But since expansion of the electrical grid is very time-consuming other strategies to maintain the rate of electrification must be considered [9]. Among these is the implementation of smart charging strategies and energy storage technology [6].

Smart charging strategies and energy storage has the potential of reducing power peaks by making it possible to shift portions of the power load to time-periods with less load on the electrical grid [10]. This would make it possible to more effectively utilize the current installed grid capacity to meet the increased power demands [6] and help to maintain the rate of electrification in society. But it also has the potential to reduce cost of buying electricity which could further increase incentive for business owners and other actors to convert to the use of electric trucks.

1.2 Aim and Research Questions

The aim of this thesis is to investigate how the implementation of smart charging strategies can reduce cost and increase flexibility for a fully electric truck depot. This will be done using historic data from a real life truck depot and linear optimization models to represent the smart charging strategies.The research questions that will be answered are the following:

- What is the power demand from a fully electrified truck depot and when does the trucks need to be charged?
- How can the electrical infrastructure of a truck depot be dimensioned for cost efficiency and flexibility?

1.3 Limitations

This study will focus on dimensioning the charging infrastructure for a single electric truck depot in the Gothenburg region. Which means that the spot price of electricity used in the investigation will be from the SE3 power zone in Sweden. The economical analysis will not compare the infrastructure and fuel cost for fossil fuel trucks but only compare variations in electrical infrastructure and charging strategies. Smart charging is a very broad concept and in this study the focus will be mainly on how smart charging can reduce cost related to investment cost of electrical infrastructure and cost of purchasing electricity.

2

Theory

In this chapter relevant theory is presented to provide a better understanding of the chosen field.

2.1 Trucks

In Sweden trucks are classified based on total weight and drivers license which can be divided into light, medium and heavy weight trucks. Light trucks have a maximum total weight of 3.5 tonnes, medium trucks have a maximum of 7.5 tonnes and heavy trucks have no maximum weight [11]. Trucks are a very adaptable transport system and highly flexible when it comes to driving destination and cargo type. This makes them one of the backbones of a modern logistical chain. Almost every single good transported will at some point be transported in a truck. The majority of trucks are today are diesel trucks but there are several fossil free alternatives. Some that are typically brought up in discussion on how decarbonize heavy-road traffic are battery electric trucks (BET), trucks driven by liquid natural gas (LNG), fuel-cell electric vehicles (FCEV) and catenary hybrid vehicles (CHV) [12]. While comparing some of these technologies it was showed that BETs had among the lowest life-cycle impact on greenhouse emissions [13]. Developing the technology and infrastructure to host BETs and in part FCEVs is also currently the focus of many major actors within the truck industry in Sweden [4].

2.2 The Swedish Electrical Grid

The Swedish electrical grid is comprised out of two main parts, the transmission grid and the distributional grid, where the distributional grid can be divided into the regional and local grid [14]. The purpose of the transmission grid is to transport electricity long distances and to connect the Swedish electrical grid with neighboring countries. It utilizes high voltages between 220-400kV to transport electricity over long distances while minimizing energy losses from resistance. The regional grid is the connecting point between the transmission grid and local grids, it works at a voltages up to 130kV. Depending on the power need of a user they can be directly connected to the regional grid. Local grids is the stretch of transport to the users and both delivers, and to a small extent receive, electricity to and from users. It works at voltages between 0.4-40kV [14]. As a result of the rapid rate of electrification the and plans to integrate more sectors to the electrical grid, *Svenska kraftnät* predicts that power demand in Sweden will increase from around 140TWh hours to 300 TWh hours in 2030 [8].

Electricity in the Nordic countries is purchased and sold using a trading platform called Nord Pool. Prices are determined by demand and supply and are set the day before electricity is produced and used. This is done in an auction where electricity producers make bids on how much electricity they can produce and buyers bid on how much electricity they want to purchase and the amount of money the are willing to purchase for. Bids are made per kWh and the highest bid sets the electricity price for that hour of the day [15].

2.3 Charging Technology

There are multiple ways to charge electric trucks at a depot. It can be done through conductive charging via either a cable, via an underbody coupler or via a pantograph. It can also be done using battery swapping or through magnetic resonance coupling [16]. But the most common and widely accepted practice is to charge through conductive charging via a charging cable. This is usually done with direct current (DC) or with alternating current (AC) [17]. Most charger models apply charging in a single direction but there are some charger models which can apply charge in two directions, these are referred to as bidirectional chargers. These charger models are generally more complex and expensive [17] but are a necessity to support vehicle to grid (V2G) systems.

Charging can generally be divided into two types of charging, AC-charging and DC-charging. Both charger types takes AC-current from local grids and converts it to DC-current to charge the battery. The difference between them is where the AC-DC conversion takes place. When using AC-charging the conversion to DC-current takes place in the onboard charging unit (OBC) which is installed in most electric vehicles. Since OBC units are mounted directly inside electric vehicles they are generally limited in size and weight due to cost and safety reasons, which limits the power capacity of AC-charging [18],[19]. Generally AC-chargers for trucks have a maximum charging level in the range between 11-22kW and are typically used for overnight charging of vehicles [18] [6]. When using DC-chargers the conversion unit is mounted outside of vehicles and charging is made directly to the battery. This way they are not limited in size as the OBC unit is. Which results in DC-chargers that have significantly higher charging capacities ranging from 22kW and higher, which are normally used for fast charging when time is limited.

Generally when speaking of the charging of electric trucks these two types of charging are combined in the European standardized combined charging system (CCS) outlet. This allows the choice of either AC or DC charging in the same cable which increases flexibility. There is also a fixed set of standards for the allowed power output, voltage and current for all types of chargers. There are several actors setting the standards but some of the most used are the ones set by the international electrotechnical committee (IEC), international organisation for standardisation (ISO) the society of automotive engineers (SAE) and charge de move (CHAdeMO) [17]

2.4 Charging Strategies

How to charge an electric vehicle can be divided into three different types. Direct charging, smart charging and bidirectional charging.

- **Direct Charging**: Electric vehicles are charged directly when parked and connected to charging cable or other charging alternative. Charging of the is ended when the vehicles reaches desired power level of the battery or when disconnected from the charging station [10]

- **Smart Charging**: A gathering word for multiple charging strategies based on the principle of shifting power loads in time. This requires some sort of communication between charging station and grid operators or energy storage of some sort to create more flexibility. It works by adjusting the power flow based parameters such as energy price, grid load and other user preferences. If implemented smart charging systems have the potential to reduce power peaks, cost of purchasing electricity and potentially mitigate the need to invest in more grid capacity [10].

- **Bidirectional Charging**: A technology that allows power to move both to and from an electric vehicle. This way vehicles batteries can serve a dual purpose by both being the power source for the vehicle and as a temporary energy storage for grid operators. This has the potential of both helping to handle variations in the power grid but also act a a source of income for vehicle owners buy being able to sell the electricity stored in the vehicles [20]

2.5 Battery Electric Storage Systems

Battery electric storage systems (BESS) is a gathering word for a system that utilizes batteries to store electrical energy. The main components are batteries and a control and powering system [21]. They serve as a flexibility resource and serve a range of different purposes such as frequency regulation, peak shaving, reduce bottlenecks and grid stabilization. Depending on the intended purpose of the BESS system the size of it can vary significantly [22].

2.6 Fuse and Switchgear

A fuse is a component that interrupts he electrical flow when overloads happen. This helps to prevent damage to electrical equipment and reduce the risk of electrical fires. Switchgear is a gathering word for a range of different electrical components used to control, protect and isolate electrical circuits. It also helps to make sure electricity is distributed correctly at a site and helps to manage the flow of electricity [23].

3

Litterature study

In this chapter relevant research and literature is presented and review to provide an overview of the chosen field.

3.1 Barriers and Drivers for Truck Electrification

Several studies have been made on the barriers and drivers for electrification of trucks and it has shown that there are many different and interconnected factors that makes the transition slow and complex. In a Swedish study by Melander et al. [7], five different freight companies operating in the urban areas of Stockholm were asked what they viewed as the main barriers and enablers for electric trucks. The chosen companies operated truck fleets of varying size, operated at different hours and delivered different types of goods. The study was made using a series of interviews and workshops where the final data was then summarized and categorized. The results presented a range of drivers and barriers interconnected with each other on an economical, societal, and social plane. Among the drivers were reduction of total cost, environmental impact and legislation. Among the barriers lack of charging infrastructure and the cost investing it it but also the worries regarding grid capacity, political uncertainties and cost issues. The results also discusses the complexity of the electrification question by highlighting the uncertainties and the fact that a driver for one firm can be a barrier for another. Another Swedish study by Gillström [24] used a similar methodology and showed similar results with a number of barriers and enablers all interconnected with each other. It did however put further emphasize on the cost impact of worsening logistical performance as a aspect that spans over multiple barriers. Especially in the transport sector where there is very little room for margin if companies want to be competitive. It did also conclude that collaboration between companies and other actors could make it easier to overcome barriers towards electrification since it was evident that all barriers could not be solved by single actors in isolation [24].

A third study by Konstatinou and Gkriza [25] applied a GREY-Demantel approach to compare and rank barriers of truck electrification with each other. It was done using survey data from 74 truck fleet managers in the U.S. This approach made it possible to identify which barriers had a larger affect on other barriers (cause barriers) and which were more affected by other barriers (effect barriers). The study implies that if policymakers chose to target the main cause barriers it could indirectly alleviate the effect barriers. The main cause barriers were found to be business model and partnership, product availability and charging time. It was also found that total cost of ownership (TCO) was a barrier of major concern but since it was also found that this barriers had no strong relationship with the other barriers. This suggests that addressing other cause barriers first can have a larger impact on the growth of electric trucks.

To summarize the findings from the studied papers it is clear that there is a will from many actors and truck fleet owners to make the transition to electric trucks. However it is clear that they are unwilling to make the transition due to large uncertainties to technology, policies and future partnerships and how this will affect the profitability and TOC of electric trucks.

3.2 The Potential of Smart Charging

In a study from PowerCircle [26] the potential of smart charging strategies in commercial transports was studied using interviews with a range of actors connected to the truck sector and smart charging infrastructure. It did also present a simplified model simulating different smart charging strategies. The study covered a range of perspectives and makes a lot of conclusions regarding the current and future potential of smart charging strategies. It states that the most commonly used smart charging strategies today are the ones focusing on reducing power peaks and ones that buy electricity based on the hourly spot price. Results from the presented model also showed that smart charging strategies can reduce the total cost of buying electricity compared to direct charging. However this was highly dependent on the choice of charging strategy, electricity supply contract and general use of vehicles. Furthermore, the study highlights a growing interest in more advanced solutions such as battery storage and participation in the ancillary service markets (through V2G technology) which can potentially provide further financial gains and more support to local grids. The study also highlights that communication and data sharing between actors is the key for a successful implementation of smart charging strategies.

The potential of smart charging with V2G technology has not yet been implemented in large scale but studies investigating the potential of economical gain using this technology shows promising results. In a study by Al-Hanahi et.al [27] smart charging strategies for heavy electric vehicles charging where vehicles charge at their home depot are modeled. The suggested strategy utilizes load management, V2G implementation and intelligent scheduling to optimize the charging of vehicles with regards to cost and reduction of peak loads. The results indicated towards substantial economic benefits while also being able to reduce peak loads up to 54%. Another study by Biedenbach and Strunz [28] achieved similar results. In this study data from a real life shipping company operating in the short haul sector was used. The study highlighted depot charging as being very suitable for the implementation of V2G-technology due to the predictable driving and charging patterns of the trucks.

The model combined many charging strategies together with internal power production from solar panels at the depot to find the optimal charging pattern for trucks parked at the depot but also account for the base load of the depot building.

A study by Lacey et.al [29] showed that smart charging strategies and V2G can be used not only to reduce peak loads, and support the local power grid but also be used as a way to prevent battery degradation. Which could otherwise could become an unwanted expense for vehicle owners. Another study by Lethola [30] investigated the impact of V2G technology and operations on the battery degradation of vehicle batteries. The study highlighted the need to develop efficient systems for how utilize V2G systems to minimize battery degradation while still being able to provide service to the grid. It also stated that smart control algorithms have the potential of compensating for the impact of additional V2G cycling.

4

Method

In this chapter the method used to answer the research questions presented in section 1.2 is described. In section 4.1 provided data regarding driving patterns and fuel consumption for depot trucks was filtered, processed and complemented to create a parking and power demand profile for a fully electric parking depot. In section 4.2 an overview model of a truck depot is generated and key components used for the charging infrastructure are identified. Two smart charging strategies were analyzed using a charging model created using a linear algebraic solver (LP) to find the most cost efficient solution. These were then compared to direct charging strategy. An overview of the work flow process can be seen in figure 4.1, where the input parameters is described in sections 4.1 and 4.2, the objective equations and charging models are described in section 4.3.

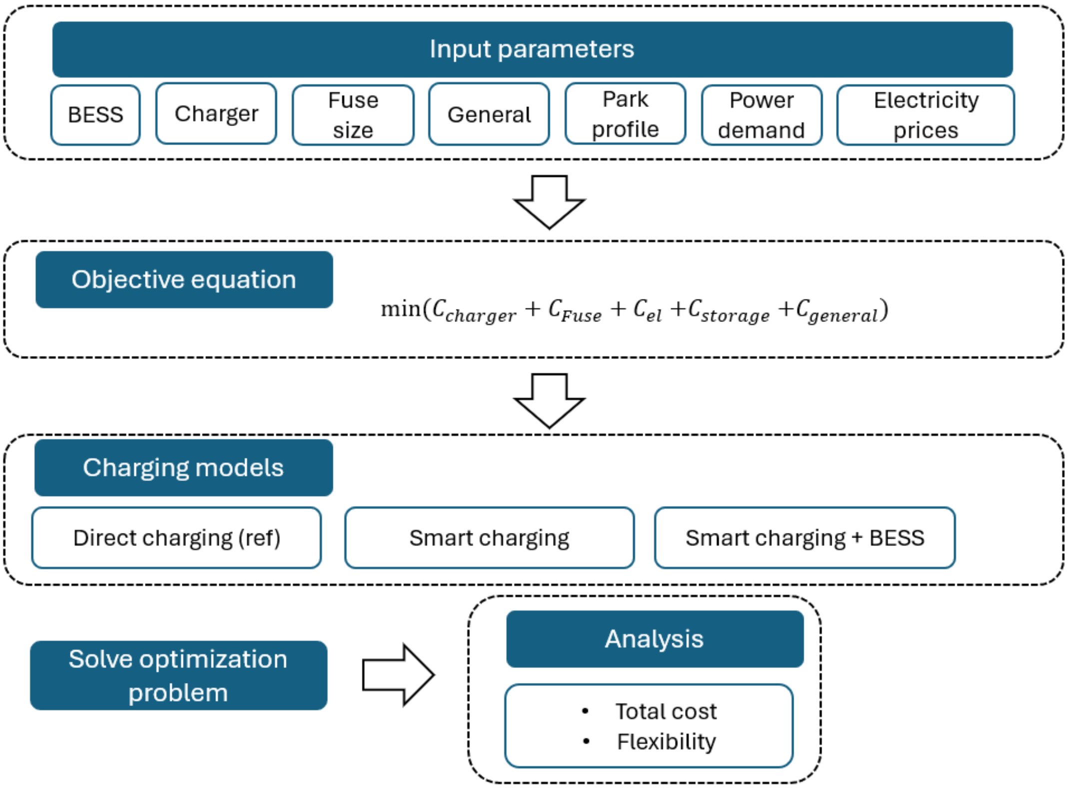


Figure 4.1: Overview of the work flow process.

4.1 Data Processing

This section presents how the provided data was filtered, processed and complemented in order to estimate a parking and demand profile for the modeled truck depot.

4.1.1 Data Description

The data used in this project was provided by one of the major logistical companies in Sweden. The company mainly manages deliveries of parcels and packages for corporations but they also make some deliveries to private customers. The company have logistical depots all over the Nordic region and use a range of different truck sizes however mainly light trucks and vans with a gross weight of 3.5 tonnes or below. The trucks in the data were all fossil fuel trucks.

The provided data was divided into three distinct parts where one part contained the raw delivery data for parcel deliveries in Sweden. The second part contained the same type of data but contained information regarding the home deliveries. The data in both sets included the deliveries from all truck depot owned by the company in Sweden and covered a full week in early autumn of 2021. For this project data from a truck depot in the Gothenburg region was used. This was done since contact with staff at this depot had been established to provide more insights regarding operations and planning. The data used to determine the parking and power demand profiles contained the following information:

1. Truck identification number
2. Time of delivery
3. Date of delivery
4. Geographical coordinates at delivery location
5. Region of delivery location
6. Postal code of delivery address
7. Gross weight of truck

Each individual truck had between zero and multiple deliveries each day. The third data set contained a summation of the companies yearly driving distance and fuel consumption for each truck for the Gothenburg depot. This was mainly used as a reference while the main calculations was made using the first two data sets.

4.1.2 Data Filtration and Processing

The data filtration and processing was made by first combining the extracted data from the two data sets. This created a new dataset containing 8258 row of unique deliveries. After filtration of corrupt data rows this amount was lowered to 8204 registered trips. Corrupt data rows included rows with the <NaN> input at the either time or geographical data points. After this all rows including a postal code not starting with the number 4 was filtered out. The assumption to remove trips with a different postcode was made based on input from staff at the Gothenburg depot informing that deliveries outside of this region do not use that depot as home base. This reduced the number of rows from 8204 to 8177 registered trips. Lastly duplicated trips registrations were removed lowering the number of registered trips from 8177 to 7065 trips. These were also filtered out based on time and geographical coordinates.

Data rows with no gross weight input were complemented with a gross weight of 3.5 tonnes. The data did not contain any registered trips to or from the depot. This was complemented with additional rows containing the geographical coordinates for the depot in the Gothenburg region and corresponding truck id. This was made with the assumption that all trucks return to the depot after driving. This increased the number of registered trips from 7065 to 7673. The driving distance between each of the registered stops was calculated using Haversine formula. This is a to calculate the shortest distance between two geographical points. The Haversine formula is presented below in equation 4.1. For each truck the sum of all trips each day was calculated to find the total driving distance each day.

$$d = 2r \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \tag{4.1}$$

ϕ - latitudinal coordinates
λ - longitudinal coordinates
r - radius of the earth in km
d - distance in km

To make the total driving distance for each truck more accurate they were compared to the third data set containing summary data for the yearly driving. This was done with the assumption that trucks operated the same way every week of the year. By sorting the data and comparing the linear trend lines with each other it was found that by complementing Haversine formula with a correction factor of 1.08. By adding a fixed driving distance of 45 km to each truck the total distance would be within 10% of the yearly average driving distances. The complemented formula can be seen in equation 4.2 below. The sum of 45 km was only added to the total driving distance and had no impact on the following calculations for the time of arrival and departure.

$$d = 1.08 \times 2r \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \quad (4.2)$$

The calculated distance was then used to estimate the time of arrival and departure to the depot for each individual truck. By assuming that driving distances below 10 km had an average velocity of 45 km/h and longer trips than this had an average velocity of 80 km/h estimations on the time of departure and arrival could be estimated. To account for loading and offloading at the depot the 50 minutes was withdrawn from the departure time, and 30 min was added to the arrival time, based on input from the staff at the depot. This way these the arrival and departure times would represent when trucks connect/disconnect from the charger.

4.1.3 Power Demand and Parking Profile

Using the estimated departure and arrival time for each individual truck a binary parking profile was generated. The non-zero input in the profile indicates that a truck is parked at the depot. The profile was generated with a 15 min timestep resolution.

Assuming all truck at the depot are electric the power demand for each individual truck was estimated by multiplying the total driven distance with an estimated average consumption based on truck type. Based on the gross weight data and feedback from the staff at the Gothenburg depot three truck types could be identified; heavy trucks, light trucks and vans. It is also assumed that all trucks within each type have the same battery size and power consumption. Estimations regarding battery size and power consumption for the three different trucks sizes can be seen in table 4.1. These estimates were based on information from staff at the depot as well as studies by Liimatainen et al. [5] and Fiori et al. [31]. The total power demand for each is shown in figure 4.2 below.

Table 4.1: Assumptions regarding truck type, battery size, power consumption.

Truck type	**Gross weight [tonnes]**	**Battery size [kWh]**	**Consumption [kWh/km]**	**Number of trucks**
Heavy	>3.5	250	0.7	3
Light	3.5	120	0.45	54
Van	<3.5	60	0.35	6

If the calculated daily power consumption for a truck exceeded the estimated battery size it was assumed that on-route charging took place during the day. The power level at arrival to the depot was therefore assumed to be 10% of the total battery capacity. It was assumed that on-route charging was only used as a measure to get back to the depot and thus only an amount large enough to get to the depot would be charged. The total power consumption for all separate days was then found by summing the power consumption for each individual truck each day.

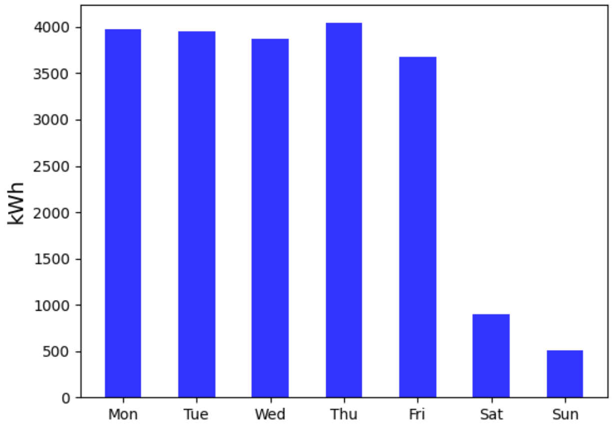


Figure 4.2: Potential power demand from all trucks for a week in September.

4.2 Depot Model and Input Parameters

In the following section a simplified overview model of a truck depot is presented. Key components managing the power supply to the chargers are presented alongside their economical and technical parameters. A simplified model of the depot is presented in figure 4.3.

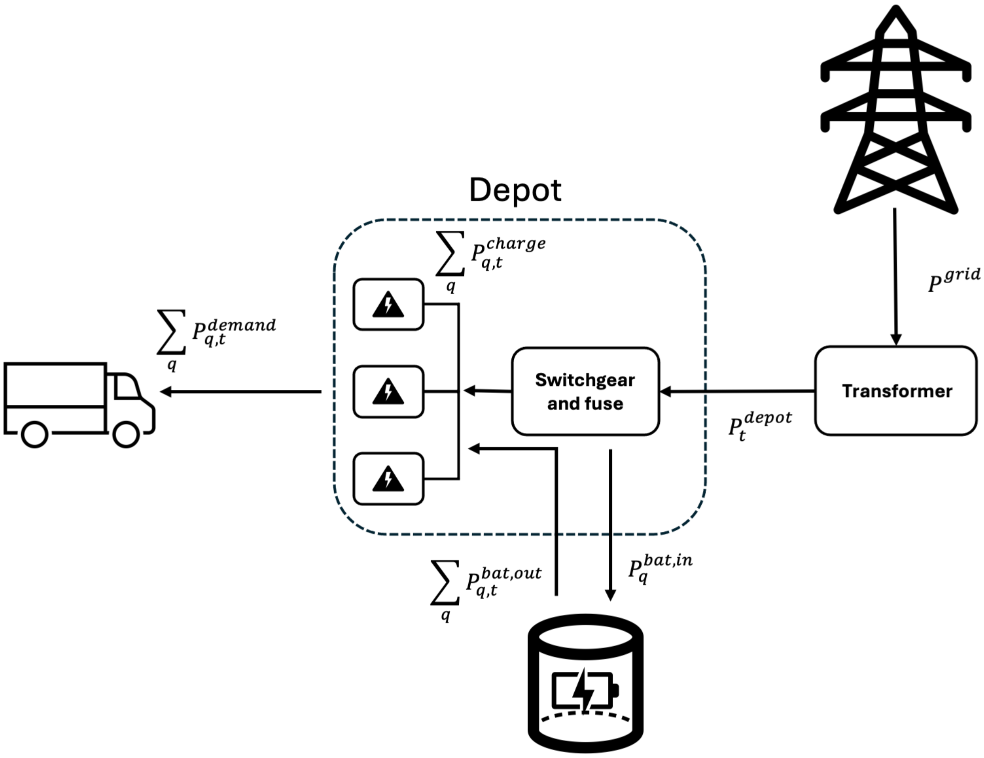


Figure 4.3: A simplified overview model of the depot model presenting the main power flows.

4.2.1 Model Parameters

Using the main power flows and components identified in depot model the technical and economical input parameters could be identified as the following.

Transformer The transformer in the model represents a transformer station owned by a local power company and is used to convert electricity from the transmission all grid to the truck depot. In this thesis the transformer is assumed to only supply the power electricity to the charging infrastructure of the depot and not include to baseload of the building or any other customers. The size of the transformer is assumed to be of 1000 kVA with a power factor (PF) of 0.95 This results in a maximum allowed hourly power of 950 kW. By also assuming that the maximum power level for normal operations$P^{max}_{tf,normal}$ is 80% of the maximum power level the limit is lower to 760 kW. The maximum power level for normal operation $P^{max}_{tf,normal}$ is calculated according to equation 4.3.

$$P^{max}_{tf} = 1000kVA \times PF \times 0.8 \tag{4.3}$$

Switchgear and fuse: Four different fuse sizes are investigated in the analysis and are presented in table 4.2. Each fuse size has an associated grid fee and the investment cost (CAPEX) of each fuse size is assumed to be 1500 SEK/A. To make the investment cost comparable to the other components the hourly annualized cost (HAC) is calculated using an assumed interest rat of 5% and an assumed technical lifetime of 30 years and the formula for annualized cost presented in equation 4.5. The maintenance and operational cost (OPEX) are assumed to be 3% of the investment cost. The calculations are made using equations 4.4 to 4.6 and the resulting cost are presented in table 4.2

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{4.4}$$

$$AC = CRF \times CAPEX + OPEX \tag{4.5}$$

$$HAC = AC \times \frac{1}{365 \times 24} \tag{4.6}$$

Battery energy storage system: Parameters for the battery electric storage system (BESS) uses an exciting model from *Hitachi Energy* as reference [34]. It has a storage capacity of 300 kWh and a discharge capacity of 300 kW.The C-rating is set to 1 meaning that it is possible to charge and discharge the battery in the span of 1 hour. It utilizes NMC Li-ion batteries and is designed for outdoor installation. The technical lifetime of a BESS battery storage unit is highly dependent the level of battery degradation which in turn is highly connected to factors such as operating temperature and charge/discharge patterns of the batteries. But since battery

Table 4.2: Fuse size, both in A and kW, grid fees and HAC values.

Fuse size [A]	**Fuse size [kW]**	**Grid fee C_f^{grid} [SEK/month]**	**HAC [SEK]**	**Source**
500	338	2865	9.63	[32],[33]
600	405	5730	14.74	[32],[33]
750	507	5730	16.44	[32],[33]
1000	676	9190	24.07	[32],[33]

degradation is not something that will be included further the technical lifetime of the BESS system will be made using the maximum number of cycles and battery state of health (SOH) alongside estimations on daily cycle use. By then using equation 4.7 a technical lifetime estimation is assumed to be approximately 10 years. This by using setting the SOH value being 70%, the total amount of cycles being 8000 and the estimated daily cycles value to 1.5. The charge and discharge efficiencies are assumed to be 96% and 90% for at total round trip efficiency of 86.4%, which is similar to the round trip efficiencies presented in [35].

$$years = \frac{SOH \times cycles_{tot}}{1.5 \times 365} \tag{4.7}$$

The investment cost of the BESS system (CAPEX) is assumed to be 400$/kWh [36]. The currency was then converted to SEK using the historic currency converter from *Svenska Riksbanken* [37].The HAC cost can be calculated using equations 4.4, 4.5 and 4.6 together with the assumed technical lifetime of 10 years and and assumed interest rate of 5%. A summary of all the BESS parameters can be seen in table 4.3.

Table 4.3: The different BESS parameters together with its respective values.

Parameter	**Value**	**Source**
Size [kWh]	312	[34]
Discharge capacity [kW]	300	[34]
C-rating	1.0	[34]
η_{charge}	0.92	[35]
$\eta_{discharge}$	0.95	[35]
HAC [SEK/hour]	21.23	-

Chargers: It is assumed that all individual trucks have access to a charger outlet when parked at the depot. Which results in a total of 63 charger units since it is also assumed that a single charger unit has a single cable connected to it. The assumption of one charger per truck was made since most truck are parked at night an switching a cable when charging is finished would not be possible due to staff working hours. The chargers are also assumed to use the standard CCS outlet. The investigated charger sizes are 22 kW AC charger and a 50 kW DC charger. The lifetime is assumed to be 10 years [18] and the charging efficiency is assumed to be 90% [18]. Cost estimations are made using a 2023 report from the Technical University of Denmark [18]. Here the investment cost for a single charger can be divided into cost of planning $C_{planning}$, cost of purchasing $C_{purchasing}$ and cost of cost of installation $C_{intstallation}$. The cost were converted from EURO to SEK using the historical average exchange rate [37] a final CAPEX value could be identified using equation 4.8. The OPEX is assumed to be 3% of the CAPEX value. The HAC value is then calculated using equations 4.4, 4.5 and 4.6. A summary of all the charger parameters can be seen in table 4.4

$$CAPEX = (C_{planning} + C_{purchase} + C_{installing}) \tag{4.8}$$

Table 4.4: The different charger parameters together with their respective values based on AC or DC current.

Parameter	**22kW AC**	**50kW DC**	**Source**
Charging capacity [kW]	0-22	0-50	[18]
$\eta_{charger}$	0.9	0.90	[18]
Planning and administration cost [SEK]	11480	17220	[18]
Investment cost [SEK]	11480	114800	[18]
Installation [SEK]	11480	57400	[18]
CAPEX[SEK]	34440	189420	-
HAC [SEK/hour]	0.52	2.86	-

Economical parameters: Alongside the hourly annualized cost of the equipment and the grid fee. There are a number of additional costs from the local energy supplier. The additional cost parameters can be seen in table 4.5 and where implemented in all models. A summary table of all cost parameters can be seen in table 4.6.

Table 4.5: The additional costs in relation to the amount/rate for each type of cost.

Type of cost	**Amount/rate**	**Source**
Energy transfer fee ($C^{transfer}_{q,t}$)	0.086 [SEK/kWh]	[32]
Price of electricity per truck (C^{el}_{q})	Depending on electricity spot price [SEK/kWh]	[32]
Energy tax ($C^{energy,tax}$)	0.439 [SEK/kWh]	[32]
Governmental fee ($C^{gov,fee}$)	8.79 [SEK/month]	[32]

Table 4.6: A summary of the economical data for each component.

Type	**Size**	**HAC [SEK/hour]**	**Grid fee C_f^{grid} [SEK/month]**
Charger	22kW	0.52	-
Charger	50kW	2.86	-
Fuse	500A	9.63	2865
Fuse	600A	14.74	5730
Fuse	750A	16.44	5730
Fuse	1000A	24.07	9190
BESS	312kWh	21.23	-

4.3 Charging Strategies

In this study three different types of charging strategies are implemented in the depot model. A direct charging strategy to be used as reference a smart charging strategy and a smart charging strategy with energy storage. Both smart charging strategies assume that electricity can be purchased based on hourly spot prices. All models use the same technical, economical and operational input parameters. During the pre-analysis it was found that there was low variation in power demand between the weekdays of the analyzed data set. It was therefore decided to make the analysis for the power demand of one single day of driving. This was done by identifying the drive and charging cycle for the all trucks driving on the chosen day. The chosen day for this was the day with the highest measured total power demand. The time period starts from 00:00 in the morning on the chosen day and ends at 18:00 the day after, resulting in a 42 hour time period. Where 00:00 represent the start of the Thursday and 18:00 is the time where the driving and parking cycle ends for the last trucks. No consideration to overlap in the driving and parking cycles where made.

All models are run using the binary parking profile $BIN_{q,t}^{park}$ alongside the corresponding demand profile, both generated from the provided driving data. The electricity prices used are historic electricity prices from 2024 for the SE3 region in Sweden. Two sets of electricity prices were used; one set with low to moderate variation represented by week 40 in September of 2024, and another set with high variations and is represented by week 50 in December of 2024. For both weeks the chosen time period is extracted. The electricity prices used can be seen in figure 4.4.

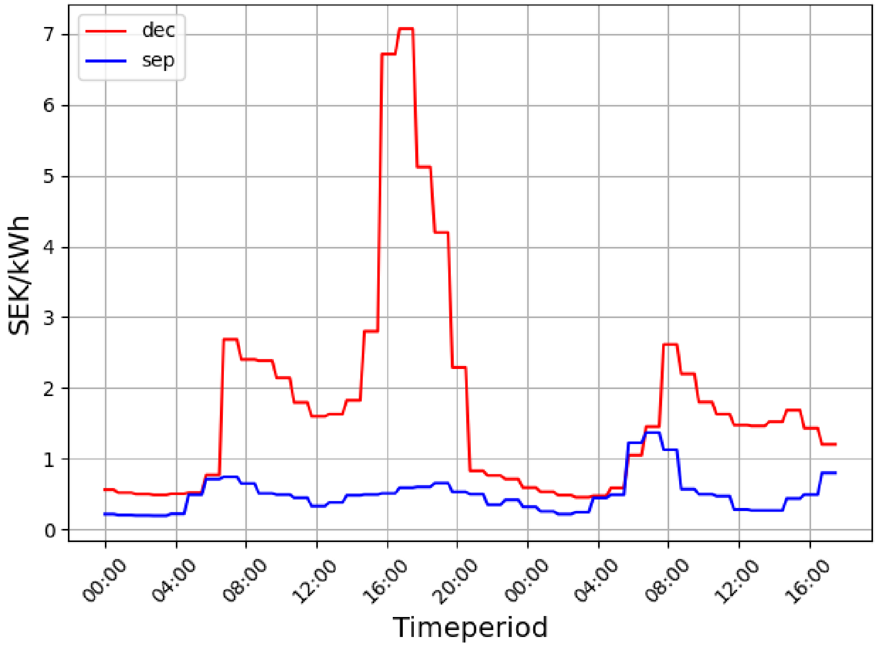


Figure 4.4: Electricity prices for 42 hour driving/parking cycle in September and December.

4.3.1 Direct Charging

Direct charging was modeled by simulating charging at full charger capacity until the power demand for the truck at the charger was met. Using the binary parking profile $BIN_{q,t}^{park}$ as indicator when trucks are parked and not parked. Constraint regarding maximum load per hour set by the fuse size P_f^{max} was handled by lowering the charge rate evenly for all parked trucks at timestep q. Charging was applied until the total demand of all individual trucks were met.

4.3.2 Smart Charging

The smart charging model is designed with the aim to reduce costs of purchasing electricity while also shifting power peaks to periods with less load on the grid. This is achieved using a LP solver together with electricity prices for the chosen time period. All sets, parameters and variables used for the smart charging can be seen in table 4.7. This table also includes the set and parameters for the smart charging with storage strategy.

Table 4.7: Sets, parameters and variables defined in equations.

Type	Symbol	Description
Sets	q	Set of time steps (15min)
	t	Set of truck id's
	c	Set of chargers
	f	Set of fuse sizes
	q_{peak}	Set of times steps during peak hours (15min)
Parameters	W_t^{demand}	Energy demand for individual truck
	P_c^{max}	Maximum allowed power for charger
	P_f^{max}	Maximum allowed power for main fuse
	$BIN_{q,t}^{park}$	Binary parking profile
	C_c^{tot}	Total cost for charger c
	C_f^{tot}	Total cost for fuse f
	C_q^{el}	Electricity price at timestep q
Variables	C_{tot}	Total daily cost of depot
	$P_{q,t}^{charge}$	Charge provided by charger to truck t at timestep q
	$C_q^{el,tot}$	Total cost of electricity timestep q
	$P_{q,t}^{bat,out}$	Power from BESS to truck t at timestep q
	$P_q^{bat,in}$	Power to BESS at timestep q
	SoC_q	State of charge for BESS system
Scalars	$C^{gov,fee}$	Governmental fees
	W_q^{BESS}	Charge & Discharge capacity for BESS

The model is centered around an objective function with the aim to lower the total daily cost C_{tot} and is described in equation 4.9 below. Here the total cost of the chargers C_c^{tot} and total cost of the main fuse C_f^{tot} are summed with the cost of buying electricity $C_q^{el,tot}$ over timestep (q). The parameter C_c^{tot} is defined as the sum of the HAC for all chargers (c) over the chosen timeperiod, represented by equation 4.10. The parameter C_f^{tot} is defined as the HAC for the fuse and the corresponding grid fee C_f^{grid}, represented by equation 4.11. The variable $C_q^{el,tot}$ includes the cost of buying electricity for all trucks (t) for all timesteps (q). It includes the energy tax $C^{energytax}$, the transfer fee $C^{transfer}$ and the governmental fee $C^{gov,fee}$ and is represented in equation 4.12.

$$min(C_{tot} = \sum_q C_q^{el,tot} + C_c^{tot} + C_f^{tot}) \tag{4.9}$$

$$C_c^{tot} = c \times C_c^{charger} \tag{4.10}$$

$$C_f^{tot} = C_f + C_f^{grid} \tag{4.11}$$

$$C_q^{el,tot} = \sum_t P_{q,t}^{charge} \times (C_q^{el} + C^{energy,tax} + C^{transfer}) + C^{gov,fee} \tag{4.12}$$

The charging behavior of the chargers at the depot can be described by equations 4.13 to equations 4.16. In equation 4.13 the energy demand W_t^{demand} for each truck individual truck (t) is met. The power demand is the power demand for the Thursday. The variable $P_{q,t}^{charge}$ represents the charge at every timestep (q) for all parked trucks. It is limited by the size of the charger P_c^{max} and the binary profile $BIN_{q,t}^{park}$ which can be seen in equation 4.14. The maximum hourly charge from all chargers combined is regulated by the fuse size P_f^{max} and is described in equation 4.15. To reduce the amount of power being purchased during peak hours equation 4.16 lowers the allowed hourly power consumption to 90% of the allowed value. According to *Svenska kraftnät* peak hours are weekdays between 08:00 to 11:00 and 16:00 to 19:00 [38].

$$W_t^{demand} = \sum_q (\eta_{charger} \times P_{q,t}^{charge}) \tag{4.13}$$

$$P_{q,t}^{charge} \times \eta_{charger} \leq \frac{1}{4} \times P_c^{max} \times BIN_{q,t}^{park} \tag{4.14}$$

$$\sum_t P_{q,t}^{charge} \leq P_f^{max} \times \frac{1}{4} \tag{4.15}$$

$$\sum_{q_{peak}} P_{q,t}^{charge} \leq 0.9 \times P_f^{max} \times \frac{1}{4} \tag{4.16}$$

4.3.3 Smart Charging with Storage

The smart charging model with storage is based on smart charging model but with a few added parameters, variables and equations to model the BESS unit. The equations used in the model are similar to the ones used in the smart charging model but with a few alterations. The objective equation is complemented with the investment cost of BESS system C^{BESS} and the charging behavior equations are complemented with the power in and out of the BESS system, $P_q^{bat,in}$ and $P_{q,t}^{bat,out}$. It is assumed that the power from the BESS goes via the chargers to the trucks and not connected separately. The altered equations are presented as equation 4.17 to 4.21 below.

$$min(C_{tot} = \sum_q C_q^{el,tot} + C_c^{tot} + C_f^{tot} + C^{BESS} \tag{4.17}$$

$$W_t^{demand} = \sum_q \sum_t (\eta^{charger} \times P_{q,t}^{charge} + P_{q,t}^{bat,out}) \tag{4.18}$$

$$P_{q,t}^{charge} + P_{q,t}^{bat,out} \leq \frac{1}{4} \times P_c^{max} \times BIN_{q,t}^{park} \tag{4.19}$$

$$\sum_t P_{q,t}^{charge} \times + P_q^{bat,in} \leq P_f^{max} \times \frac{1}{4} \tag{4.20}$$

$$\sum_{q_{peak}} P_{q,t}^{charge} + P_q^{bat,in} \leq 0.9 \times P_f^{max} \times \frac{1}{4} \tag{4.21}$$

The model is also complemented with equations to model the operating behavior of the BESS. The initial value of the SoC variable for the BESS system is set by the model but has to be the same at the first and last timestep according to equation 4.24. The state of charge at timestep q $SoC_q$is also limited to vary between 20% and 80% of the maximum storage level of the BESS system $P^{BESS,max}$ as shown in equations 4.22 and 4.23. Which is done to consider battery degradation to an extent. The dynamic between the power in and out of the BESS system is shown in 4.25 where also the assumed charge and discharge efficiencies $\eta_{bat,in}$, $\eta_{bat,out}$ of the system are implemented. Lastly the amount of charge and discharge from the BESS system is regulated by equations 4.27 and 4.26.

$$SoC_{max} \leq 0.8 \times P^{BESS,max} \tag{4.22}$$

$$SoC_{min} \geq 0.2 \times P^{BESS,max} \tag{4.23}$$

$$SoC_{q=1} = SoC_{q=168} \tag{4.24}$$

$$SoC_q - Soc_{q-1} = \eta_{bat,in} \times P_q^{bat,in} - (\sum_t P_{q,t}^{bat,out}) \times \frac{1}{\eta_{bat,out}} \tag{4.25}$$

$$(\sum_t P_{q,t}^{bat,out}) \times \eta_{bat,out} \leq W_q^{BESS} \times \frac{1}{4} \tag{4.26}$$

$$P_q^{bat,in} \times \frac{1}{\eta_{bat,in}} \leq W_q^{BESS} \times \frac{1}{4} \tag{4.27}$$

4.3.4 Modeled Scenarios

To investigate how the total cost changes during different operating conditions a series of case studies were made where all combinations of charger size, fuse size, charging strategy and electricity prices were made. This resulted in a total of 48 case scenarios. A summary of all combinations can be seen in the Appendix A.1.

Flexibility for all modeled scenarios is measured as the total energy demand from all trucks $\sum W_t^{demand}$ divided with the sum of potential energy that the chargers can provide $\sum W_{t,c}^{potential}$. This potential energy is the the total amount of energy a charger can charge with regards to the time a truck is parked by the charger. This is described in equation 4.28 below.

$$Flex_{index} = \frac{\sum W_t^{demand}}{\sum W_{t,c}^{potential}} \tag{4.28}$$

5

Results

In this chapter the results from the the modeled scenarios are presented. The results are divided into two main parts. Section 5.1 presents the results answering the question on how driving and demand profiles of a fully electric trucks depot could look like. Section 5.2 presents results of how dimensioning of different components and charging strategy will affect cost and flexibility.

5.1 Parking and Demand Profile

By analyzing the departure and arrival times to the depot for all days in the provided dataset it was found that the trucks spend a long period of time parked at the depot. The average time spend parked after arrival was found to be approximately 18 hours and the average time spent driving each day was found to be approximately 5 hours and 20 min. The average time of arrival after driving is around 15:38 and the average departure time is approximately at 10:17. The number of truck parked at each timestep of the analyzed driving and parking cycles can be seen in figure 5.1 together with the total parking time for each truck at the depot in figure 5.2. The number of trucks parked from the time period of Monday 00:00 to Friday 24:00 can be seen in the Appendix A.2. The distribution of parked trucks at the depot over the analyzed driving/parking cycle is visualized in figure 5.3 below.

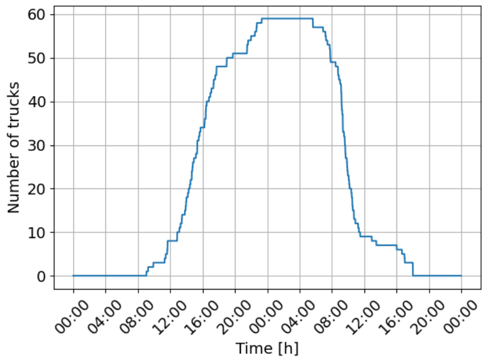


Figure 5.1: Number of trucks parked at depot over 42 hour driving/parking cycle

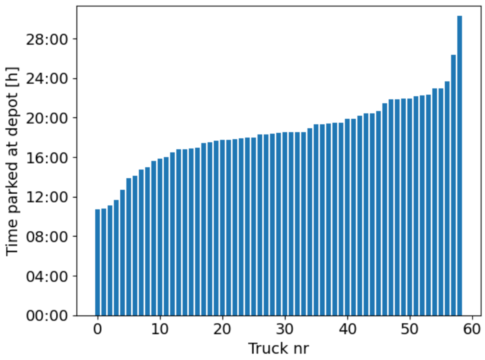


Figure 5.2: Time parked at depot for each individual truck over 42 hour driving/parking cycle

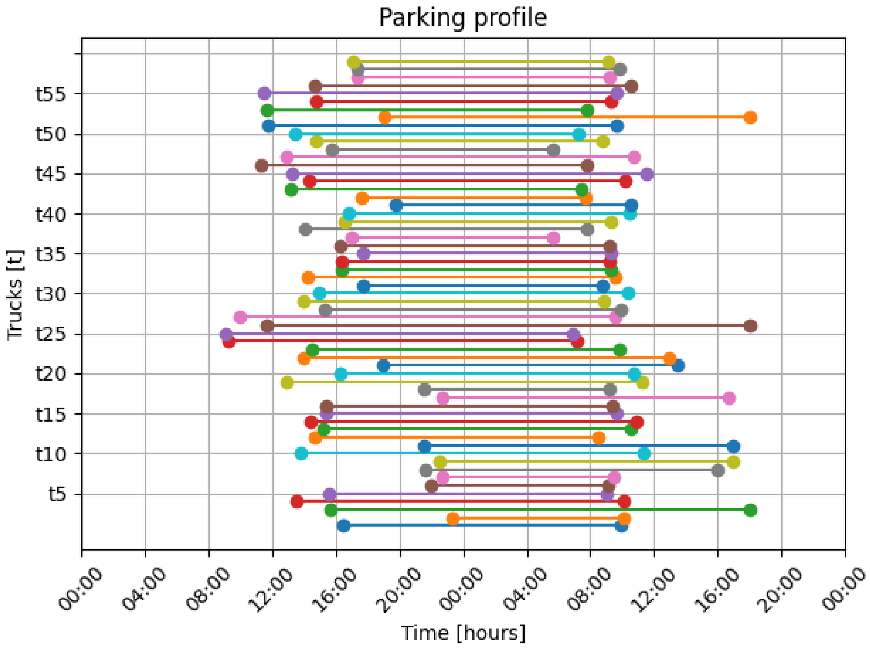


Figure 5.3: Parking profile over 42 hour driving/park cycle.

The energy consumed during driving for the chosen day varied significantly between individual trucks and can be seen in figure 5.4. It was also found that ten trucks were assumed to perform on-route charging since their energy consumption exceeded their battery size. This resulted in their state of charge (SoC) upon arrival at the depot was assumed to be 10% of their battery size. The average energy used for each truck was found to be 79.78 kWh. By dividing the energy consumption of a single truck and dividing it with the time the truck is parked at the depot a value of the average charging power could be calculated. The mean average charging power rate for all trucks was found to be 3.92 kW and the highest was found to be 11.2 kW. An overview of the average power rates for all trucks can be seen in figure 5.5.

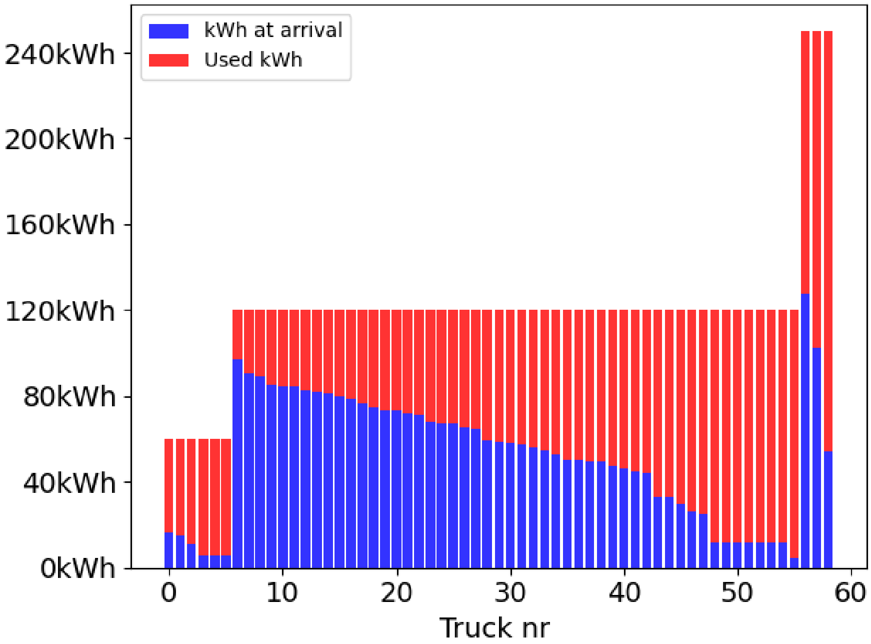


Figure 5.4: Energy levels of truck battery upon arrival at the depot over 42 hour driving/parking cycle

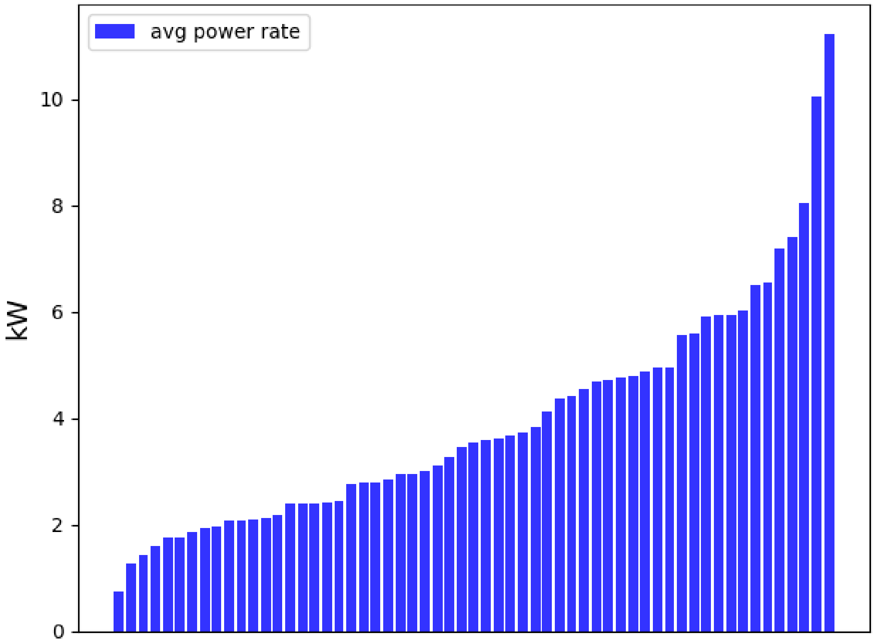


Figure 5.5: Average charging power rate of all individual trucks during 42 hour driving/parking cycle

5.2 Cost Optimization and Flexibility

In this section the cost structure for all modeled scenarios is presented. It also contains a cost and flexibility comparison between the three charging strategies together with general findings of the analysis.

5.2.1 Direct Charging Strategy

The cost structure for the depot for all scenarios implementing the direct charging model can be seen in figure 5.7 and 5.6 below. In the modeled scenarios using the September electricity prices and the 22 kW chargers the cost is dominated by the cost of electricity and when using the 50 kW chargers the cost is dominated by the cost of the chargers. In the scenarios with the December electricity prices the total cost is dominated by the cost of purchasing electricity regardless of charger size. For both electricity prices there is no clear relation between the total cost of the system and and the size of the fuse and chargers. Which can be explained by the model not having any flexibility to shift the load. Since it the model has no flexibility the total cost is highly dependent on the spot price of electricity and there is no clear economic gain in investing in more charging capacity than needed. Which corresponds well with the results where the smallest charger (22 kW) size in combination with the smallest fuse size (500 A) is most cost effective for both electricity prices.

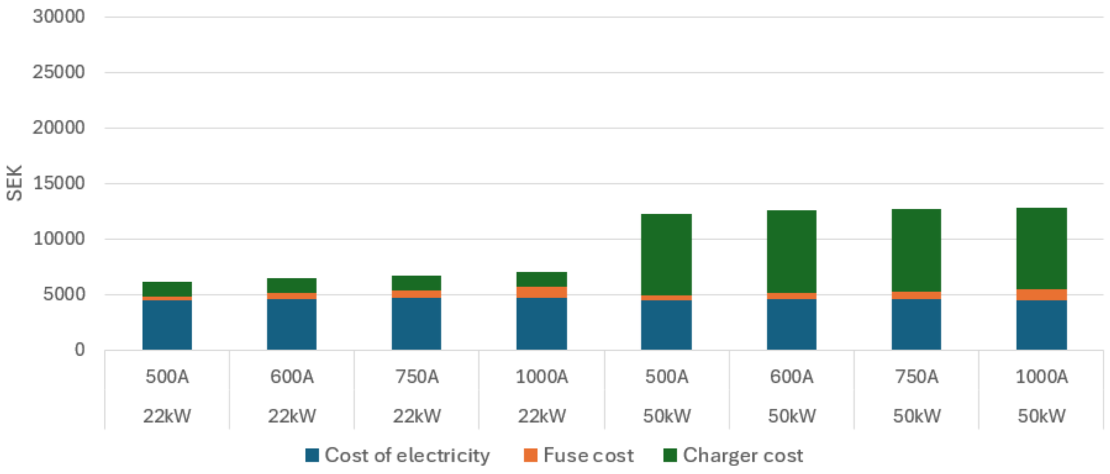


Figure 5.6: Direct charging: Cost structure for 42 hour driving/parking cycle using September electricity prices.

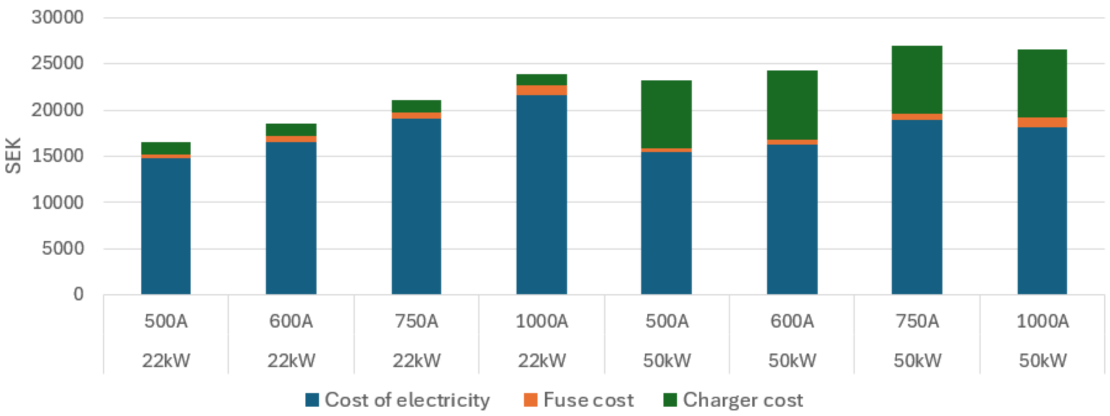
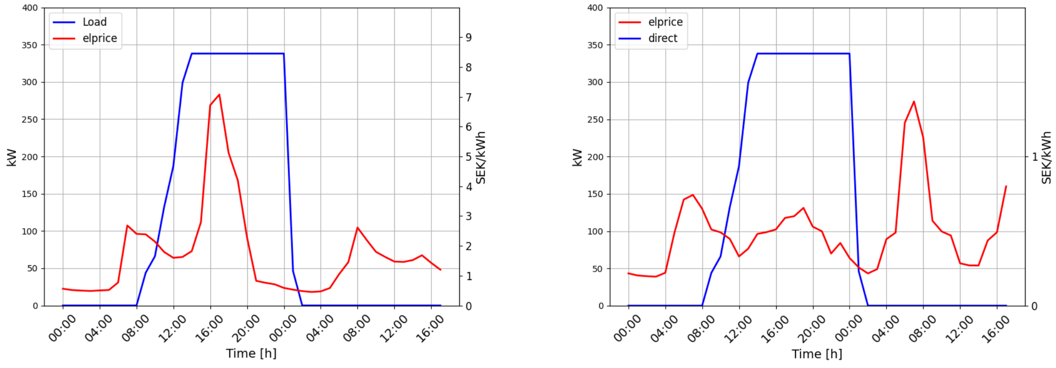


Figure 5.7: Direct charging: Cost structure 42 hour driving/parking cycle using December electricity prices

The power load from charging at the depot using a 22 kW charger, a 500 A fuse and both electricity prices electricity prices can be seen in figure 5.8. The blue line represents the modeled charging load and the red line represents the variations in the spot price of electricity over the chosen 42 hour driving/parking cycle.



a) **b)**

Figure 5.8: Direct charging load using 22 kW charger and 500 A fuse and electricity prices from **a)** December and **b)** September

5.2.2 Smart Charging Strategy

The cost structure for the depot for all modeled scenarios implementing the smart charging strategy can be seen in figure 5.10 and 5.9 below. In all scenarios where the 50 kW charger was used the increased investment cost did not reduced the cost of electricity enough to justify the increased investment cost. Resulting in no scenario where the choice of using the 50 kW charger had a lower total cost than using the 22 kW charger. This can be seen in figures 5.10 and 5.9 below. The results also indicates that investments in a larger fuse size can reduce the cost of electricity $C_q^{el,tot}$ to the extent that the increase investment cost of the fuse will still be profitable. But only when simulating case scenarios using the December electricity prices.

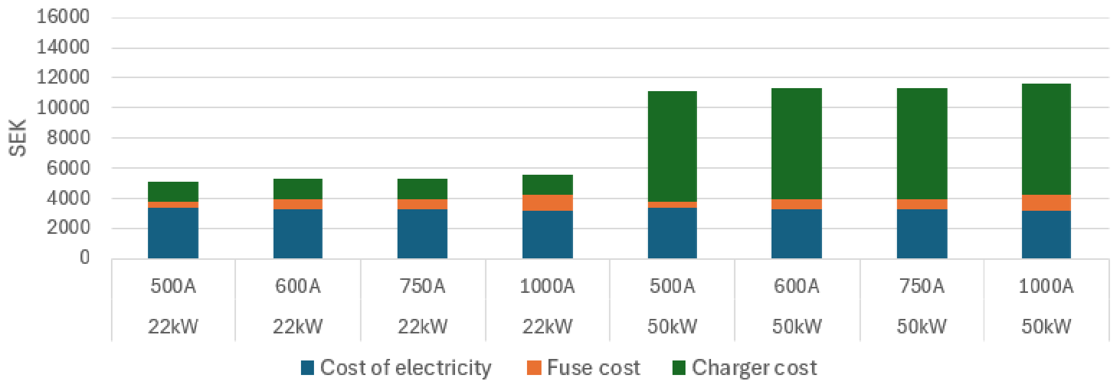


Figure 5.9: Smart charging: Cost structure over 42 hour driving/parking cycle, September scenarios

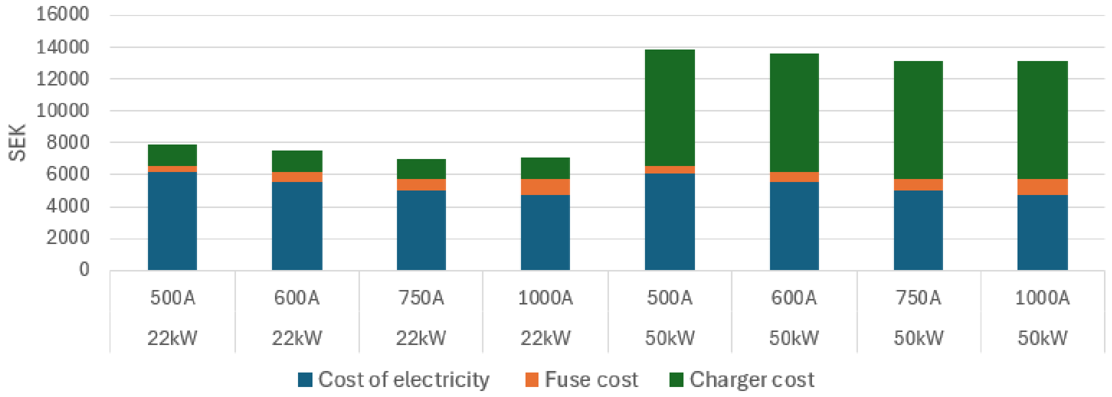


Figure 5.10: Smart charging: Cost structure over 42 hour driving/parking cycle, December scenarios.

The economical and flexibility impact on increasing the fuse size for both electricity prices can be seen in table 5.1. The most cost efficient combination of charger and fuse size when modeling the September electricity prices was a 22 kW chargers and a 500 A fuse. The best combination when modeling the December electricity prices was 22 kW chargers and a 750 A fuse.

Table 5.1: The impact of the fuse size on flexibility index and cost structure for December and September electricity prices, with the use of smart charging strategies

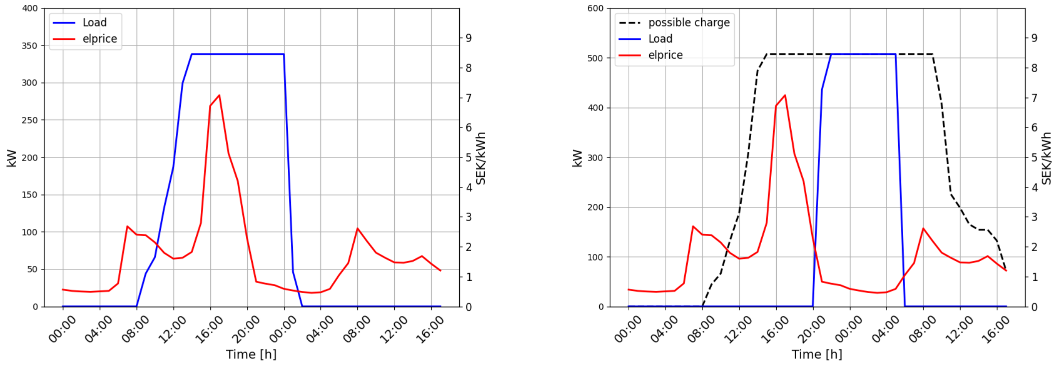
Electricity price	**Fuse size**	**Flex index**	**Electricity cost [SEK]**	**Inv cost [SEK]**	**Total cost [SEK]**
Dec	500 A	1.9	6134	404	7861
Dec	600 A	2.29	5556	619	7499
Dec	750 A	2.75	5006	690	7019
Dec	1000 A	3.46	4739	1011	7073
Sep	500 A	1.9	3349	404	5076
Sep	600 A	2.29	3311	619	5254
Sep	750 A	2.75	3260	690	5274
Sep	1000 A	3.46	3231	1011	5565

When comparing the smart charging model and the direct charging model the cost of buying electricity is significantly reduced, which is a result of introducing flexibility in the system by allowing the charging load to be shifted to hours with a lower spot price of electricity. By comparing the two charging strategies it can be seen that the total cost of the system can be reduced between up to 58% with the introduction of smart charging strategies and enough variation in the spot price of electricity. A cost comparison of the two charging strategies can be seen in table 5.2. In the comparison the scenarios with the lowest total cost for each charging strategy are compared, this is done for both the September and December spot prices of electricity. Investment cost in the table refers to the sum of the chargers and fuse costs.

Table 5.2: Comparison of scenarios with lowest total cost

Charging model	**Elprice**	**Cost of electricity [SEK]**	**Inv cost [SEK]**	**Total cost [SEK]**
Direct	Sep	4461	1727	6188
Smart	Sep	3349	1727	5076
Diff	Sep	-1112	0	-1112
Direct	Dec	14818	1727	16545
Smart	Dec	5006	2013	7019
Diff	Dec	-9812	286	-9526

The corresponding charging loads for each charging strategy using the December electricity prices can be seen in figure 5.11. The dashed black line represents the potential charging power level with regards to when trucks are parked at the depot.



a) **b)**

Figure 5.11: Charging load, electricity prices and possible charge using December electricity price over 42 hour driving/parking cycle **a)** Direct charging **b)** Smart charging

5.2.3 Smart Charging with Storage Results

The cost structure of all the modeled smart charging with storage scenarios can be seen in figure 5.13 and figure 5.13 below. As with the other charging strategies the use of the 50 kW chargers did not prove to be cost efficient in comparison to using the 22 kW chargers. The most cost efficient combination of charger and fuse size when modeling the September electricity prices was a 22 kW chargers and a 500 A fuse. The best combination when modeling the December electricity prices was 22 kW chargers and a 750 A fuse. Which are the same combinations that was found when investigating the smart charging strategy.

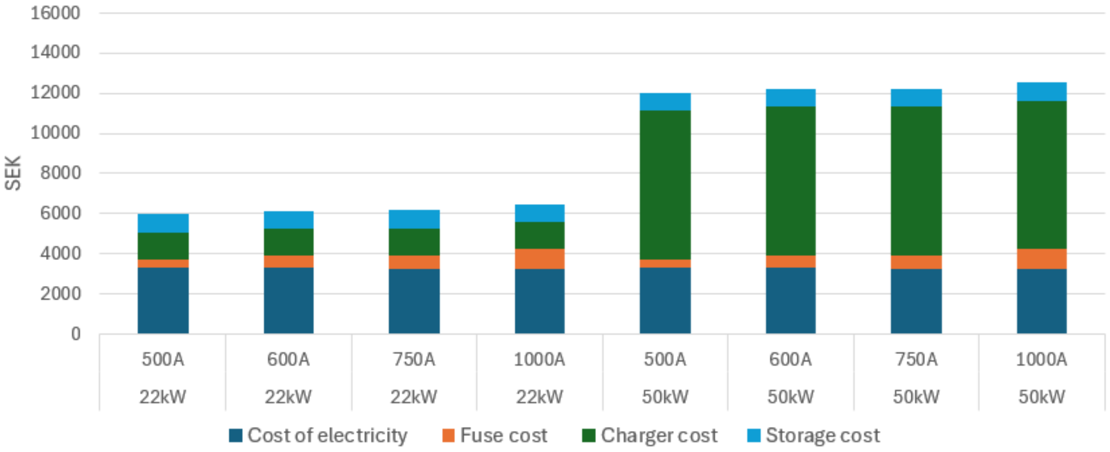


Figure 5.12: Smart charging+BESS: Cost structure for 42 hour driving/parking cycle, September scenarios.

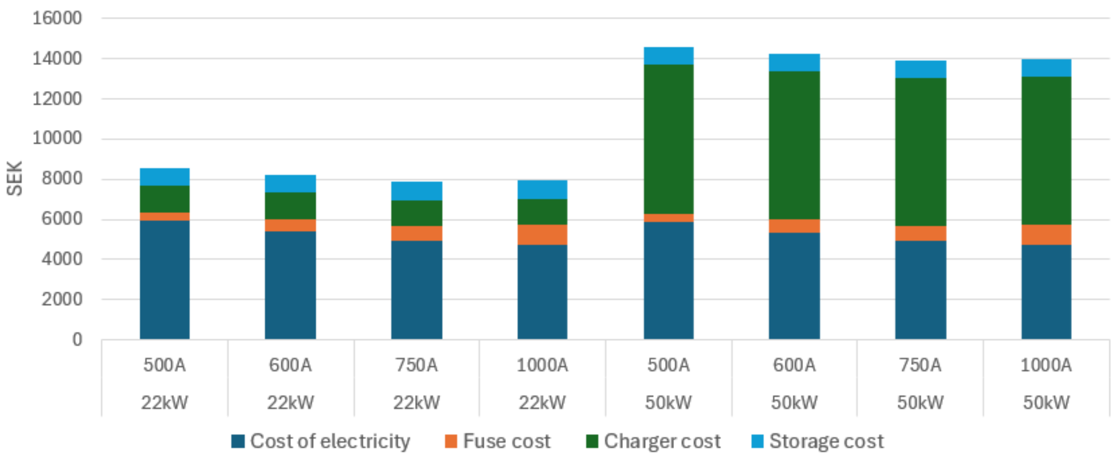


Figure 5.13: Smart charging+BESS: Cost structure for 42 hour driving/parking cycle, December scenarios.

A comparison of cost and flexibility of the smart charging strategy with and without the BESS can be seen in table 5.3. In the comparison the scenarios with the lowest total cost for each charging strategy are compared, this is done for both the September and December spot prices of electricity. Investment cost in table 5.3 refers to the cost of chargers, fuse and BESS. In table 5.3 it is possible to see that the increase in investment cost caused by implementing a BESS system will only reduce the cost of buying electricity minimally. The small reductions in the cost of buying electricity is a direct cause of the BESS system being able to charge regardless of trucks being parked at the depot or not. This means that part of the charging can take place over a longer time period which in turn means that more variations in the spot price of electricity can be considered to further reduce to cost of buying electricity. The increase in flexibility by installing a BESS system was only marginal due to the small size of the BESS system in comparison with the total energy demand from the trucks. It was also affected by the high levels of flexibility in shifting the charging load already made possible by utilizing the 22 kW chargers, which made the need for a storage unit superfluous.

Table 5.3: Comparison of case scenarios with lowest total cost.

Charging model	**Elprice**	**Flex index**	**Cost of electricity [SEK]**	**Inv cost [SEK]**	**Total cost [SEK]**
Smart	Sep	1.98	3349	1727	5076
Smart+BESS	Sep	2.05	3341	2618	5717
Diff	Sep	0.07	-8	891	641
Smart	Dec	2.74	5006	2013	7019
Smart+BESS	Dec	2.81	4944	2823	7849
Diff	Dec	0.07	-62	810	830

The corresponding charging loads for each charging strategy using the December electricity prices can be seen in figure 5.14. The dashed black line in the plot with smart charging+BESS represents the potential charging power level with regards to when trucks are parked at the depot and when the BESS is able to charge. By comparing the two plots in figure 5.14 it is possible to see that part of the charging load can be shifted to a period where no trucks are parked at the depot. The corresponding SOC dynamic of the BESS system in the scenario presented in figure 5.14 can be seen in figure 5.15. In figure 5.15 the blue line represents the SOC of the BESS in kWh and the dashed black line represents the maximum and minimum allowed energy levels of the BESS.

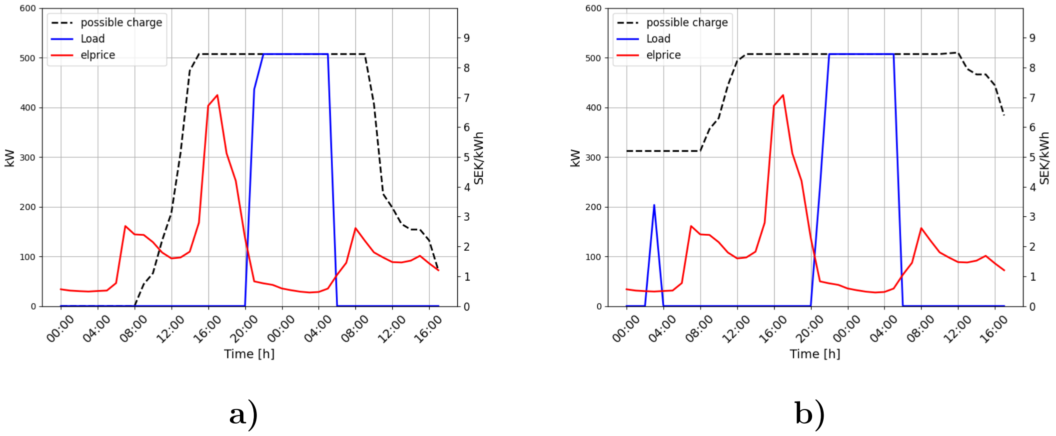


Figure 5.14: Charging load, electricity price and possible charge using December electricity prices over 42 hour driving/parking cycle **a)** Smart charging **b)** Smart charging with BESS

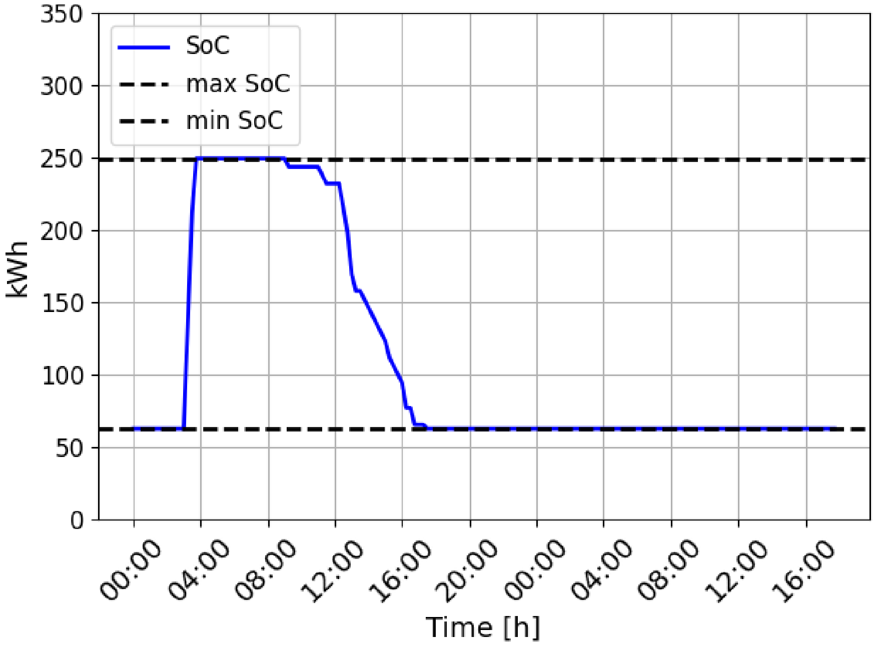
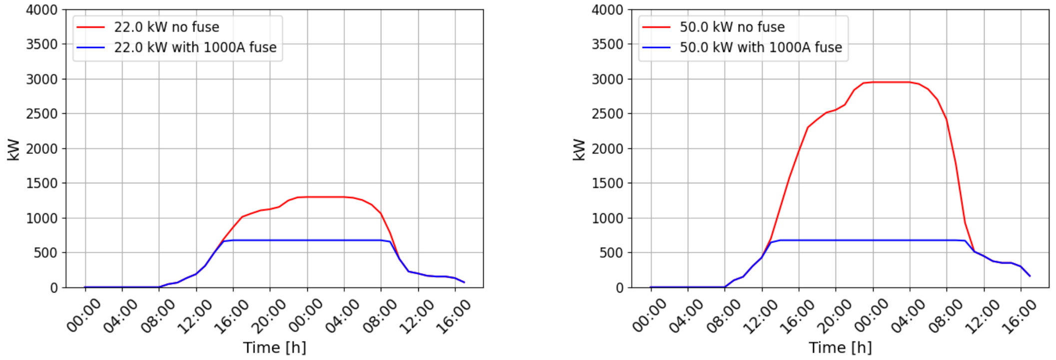


Figure 5.15: SOC dynamic of BESS over 42 hour driving/parking cycle

5.2.4 Result Summary

The results of the analysis shows that there are benefits with flexible charging and that investment in components that allow the charging load to be shifted in time. It was found that flexibility by increasing the fuse size was the most cost efficient in comparison to increasing the charger size or implementing a BESS system. The reason for the fuse being the governing component is a direct result of the binary parking profile, amount of chargers and the charger sizes investigated. In figure 5.16 two plots are presented, one representing the potential charging at the depot using the 22 kW chargers and one representing the 50 kW chargers. The red line represent all charger at the depot operating at full capacity with regards to the binary parking profile. The blue line represents all charger at the depot operating at full capacity with regards to both the binary parking profile and the fuse size. For both plots the fuse size is assumed to be 1000 A. By comparing the two plots in figure 5.16 it can be seen that neither none of the chosen charger sizes can be utilized to its full extent due to limitations set by the fuse. It can also be seen that more of the potential of a 50 kW charger is lost compared to the 22 kW charger. This indicates that the concentrated time period where all trucks are parked at the depot makes investments in fuse size provide more flexibility compared to investing in higher charger capacity since it cannot be utilized.



a) **b)**

Figure 5.16: Potential at depot with 1000 A fuse over 42 hour drving/parking cycle using **a)** 22 kW charger and **b)** 50 kW charger.

6

Discussion

This chapter presents a discussion of the main results and used methods, discuss uncertainties and suggest possible measures for future investigations. In section 6.1 the parking and power demand profile are discussed. In section 6.2 the depot model and charging strategies are discussed.

6.1 Parking Profile and Power Demand

The staff at the Gothenburg truck depot estimates that all their trucks leave between 07:00-09:00 in the morning and return again around 15:30-18:00 the same day. It was also estimated that some evening deliveries in the time period of 18:00-21:00 take place. The exact times depends on the type of delivery. This differs to an extent from the calculated average arrival and departure times presented in section 5.1. The most probable causes for this is the initial filtration and processing of the data presented in section 4.1. Where the filtration, complementing calculation and interpretation of data has failed to account potential evening deliveries and produced non-accurate arrival and departure time values. However the results were deemed to be accurate enough to be used in this project but they cannot be considered to be an accurate representations of reality. To achieve more accurate results it suggested to utilize some sort of GIS software when making the calculations. Another alternative approach is to make a new data collection where only power consumption, battery size, driving distance and time of arrival and departure are measured. Which would remove the need for the supplementary calculations made in section 4.1.

The time period of 42 hours used in the analysis was chosen based on the driving and parking cycles of all trucks driving on the day with the highest power demand. This provided the charging models with good margins when distributing the load for each truck, utilized variations in the electricity price and allow for the BESS system to operate effectively. However this approach fails to consider the overlap of parked trucks at the depot and how this affect the distribution of electricity for the chargers. The overlap is caused by some truck arriving at the depot before others depart and the opposite. This means that over the analyzed driving and parking cycle there are some trucks that start their second driving period within this time period. The overlap is clearly visible in figure 6.1 showing when trucks are parked from Thursday 00:00 to Friday 00:00. The overlap would most likely not have a significant impact on the models ability to meet the charging demand for each individual truck but would impact how the charging load is distributed and thereby have an affect on the total cost of purchasing electricity and amount of flexibility. This issue could be solved by adapting the model to work with longer time periods which would consider the overlap. Investigating longer time periods could also increase the accuracy of the cost estimations since seasonal and yearly variations of the electricity price could be considered. Analyzing a time period over the course of one full year could be beneficial since it would cover weekly, monthly and seasonal variations.

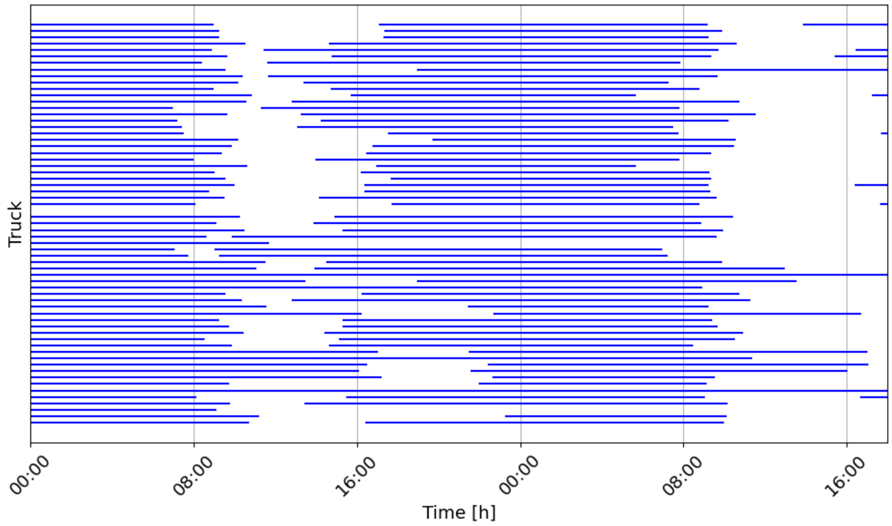


Figure 6.1: Overlap of parked trucks Thursday to Friday

6.2 Charging Models

The depot model presented in section 4.2 is an simplified overview model of the electrical infrastructure of a truck depot. The assumption that the transformer in the system only supplies electricity to the charging infrastructure of the depot is reasonable since many larger industries can have multiple grid connection points. But this approach fails to take the baseload of the depot building into account. The baseload would include the power demand for heating, electrical equipment, lighting and other equipment used on an everyday basis. By not including the baseload the full load impact of the truck depot has not been determined which will have impacted the final results of the charging models by allowing for more flexibility when shifting the power loads. Including the baseload in future analysis would most likely even out variations in total cost of electricity between the charging models since it would reduced flexibility. Which could affect the dimensioning of the charger and fuse size.

Results from the analysis clearly show that the the full charging capacity of the 22 kW and 50 kW chargers are not fully utilized. Which indicates that a smaller charger size could be used more effectively in regards to its power capacity and to reduce investment costs. This would however minimize the margin between the rated power capacity of the charger and the average power need of the trucks. Which would go against the recommendations found in literature [18] since the highest average power rate was found to be 11.2 kW. It is also reasonable to assume that the inaccuracies in the calculated parking and power demand profiles together with the assumption of no base load from the depot buildings will have increased the flexibility of the system. Which most likely results in an overestimation of the flexibility of the system for both modeled scenarios. To achieve a more optimized system it would be of interest to investigate how a mix of charger or shared charging points could affect the depot. But then further investigation to scheduling of truck operations would be needed.

The results did point towards increasing the fuse size being a cost efficient way for depot owners to increase flexibility and reduce cost. But if several actors increase their fuse size it can cause problems for local electricity producers and grid owners. Especially if the increased capacity is not utilized to its full capacity but only for shorter periods of time. Which could result in grid planners having to plan for the potential of increased power consumption and potentially make costly unnecessary reinforcement of the grid and make sure power can be supplied. Eventually resulting in higher cost for the customer [39]. A larger fuse size will result in larger power peaks from the depot which could potentially lead to additional cost with the implementation of power tariffs. Power demand tariffs are generally based on a monthly basis are therefore not include in this project due to the short time period analyses. But it would be relevant to investigate their economical impact in future analysis since Swedish power companies are by law required to implement power demand tariffs [40].

The implementation of the BESS unit allows for charging even when trucks are not parked and results indicate that this will further reduce the cost of electricity, however the results are slightly shifted due to the fact that the model chooses the initial SOC value for the BESS system and does not take the operations of the previous day into account. The increased cost reduction is also minimal and not enough to compensate for the investment cost of the system. The reason for this can be that there already is enough flexibility in the system already provided by the chargers and fuse which makes the implementation of a BESS system redundant. For the BESS to provide actual economical benefits it would most likely be in scenarios where flexibility in the system is more limited. It could for example prove to be cost effective to use a BESS system effectively together with an even smaller charger size than the ones investigated in this project or if the base load of the depot would have been considered. A BESS system could also serve a dual purpose by providing ancillary services to the grid in form of voltage and frequency regulation or enable a more effective use of complementary renewable power production at a depot [22]. This is not something that have been investigate in this project but it has the potential of making it more beneficial to install a BESS system from both a cost and load perspective.

7

Conclusion

The aim of this study was to investigate how smart charging strategies could reduce cost and increase flexibility for a fully electrified truck depot. This was answered by determining when and for how long trucks stay parked at the depot and the energy need of each truck. By then modeling two smart charging strategies and comparing them with a direct charging strategy some conclusion could be made. From this this study it can be concluded that the implementation of smart charging strategies at fully electric trucks depots has the potential of reducing the cost of electricity substantially compared to direct charging strategies. They also indicate that investments in electrical infrastructure at the depot to increase flexibility can be profitable, but only if there is enough variation in the spot price of electricity. It was found that investments in larger fuse sizes to increase the maximum allowed power level from charging at the depot was most cost efficient in comparison the increasing the capacity of each individual charger. Which is a result of the concentrated time period where trucks are parked. However,the number of assumptions regarding the calculated parking profile and power demand from the trucks cannot be considered to be accurate representation of reality. This in turn will have impacted the results of the modeled scenarios making the result inconclusive. The lack of a more in depth technical analysis of the charging infrastructure at the depot and an economical analysis accounting for longer time periods will also have had an impact on the inconclusiveness of the results. Further research with a more comprehensive and specific data collection and a more robust method of analysis would therefore be needed to draw a more clear conclusion. Despite the flaws and limitations of this work it can serve as a foundation for future studies within the topic of electrification and truck depots.

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A

Appendix 1

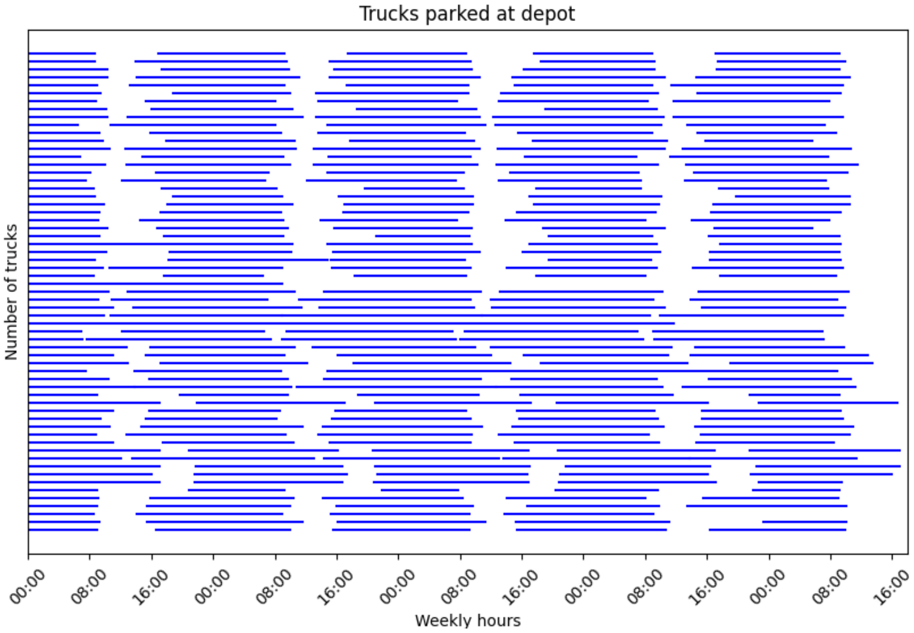

Figure A.1: Visualization of when trucks are parked during time period Monday 00:00 to Friday 00:00 of the analyzed week

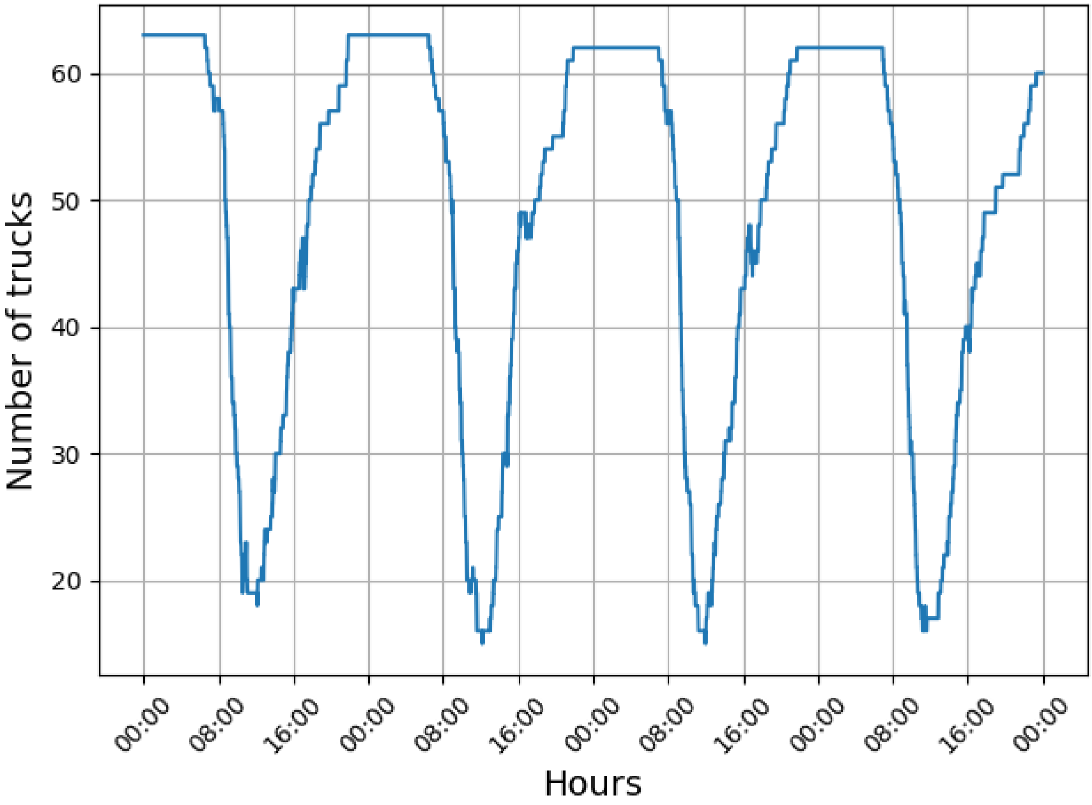

Figure A.2: Number of trucks parked during time period Monday 00:00 to Friday 00:00 of the analyzed week

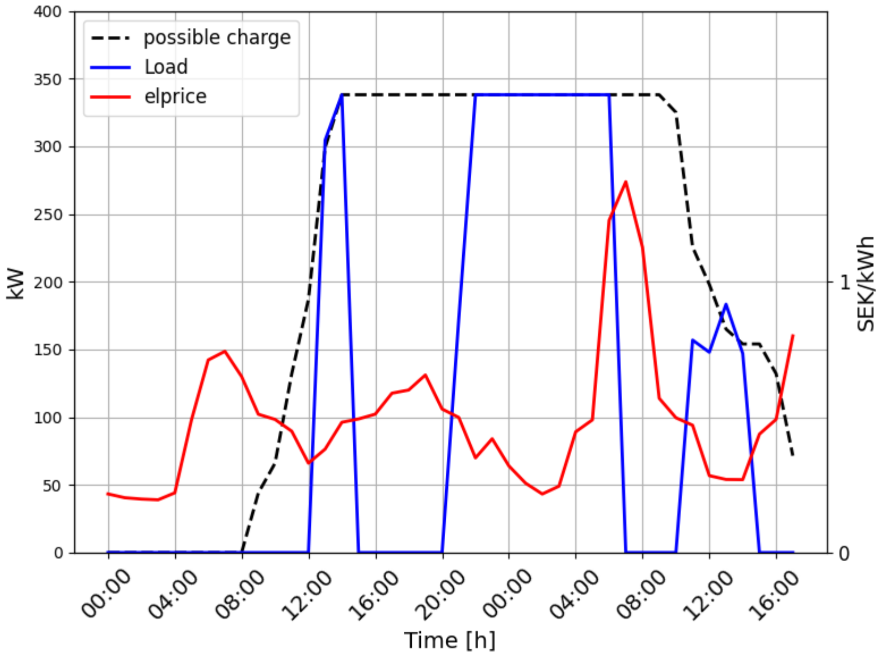

Figure A.3: Smart charging: Charging load and electricity price using September electricity prices over 42 hour driving/parking cycle. Using a 22 kW charger, 500 A fuse

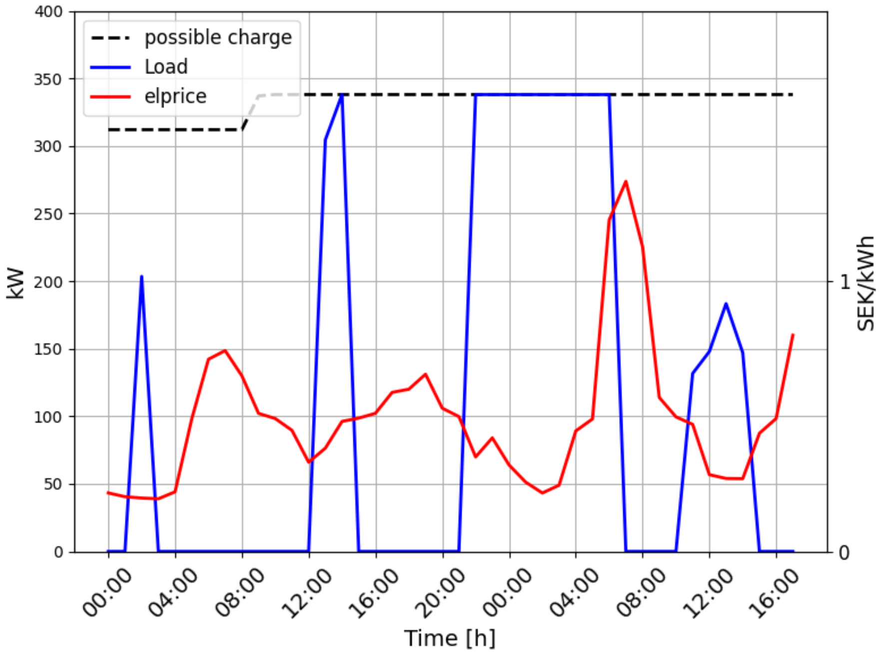

Figure A.4: Smart charging+BESS: Charging load and electricity price using September electricity prices over 42 hour driving/parking cycle. Using a 22 kW charger, 500 A fuse

Table A.1: Comparison of case scenarios with lowest total cost

Case scenarios	**Electricity Price**	**Charging strategy**	**Charger size [kW]**	**Fuse size [A]**
1	sep	direct	22	500
2	sep	smart	22	500
3	sep	smart+storage	22	500
4	sep	direct	50	500
5	sep	smart	50	500
6	sep	smart+storage	50	500
7	sep	direct	22	600
8	sep	smart	22	600
9	sep	smart+storage	22	600
10	sep	direct	50	600
11	sep	smart	50	600
12	sep	smart+storage	50	600
13	sep	direct	22	750
14	sep	smart	22	750
15	sep	smart+storage	22	750
16	sep	direct	50	750
17	sep	smart	50	750
18	sep	smart+storage	50	750
19	sep	direct	22	1000
20	sep	smart	22	1000
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27	dec	smart+storage	22	500
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40	dec	direct	50	750
41	dec	smart	50	750
42	dec	smart+storage	50	750
43	dec	direct	22	1000
44	dec	smart	22	1000
45	dec	smart+storage	22	1000
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47	dec	smart	50	1000
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