
An Evaluation of Charging Technologies for Heavy-Duty Electric Vehicles from an Economic, Technical and Environmental Perspective

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Abstract

The transportation sector is heavily reliant on fossil fuels and accounts for a significant share of global CO₂ equivalent emissions. To address this, electrification of transport is a strategy stated by the European Commission and the Swedish government. A transition towards an electrified transportation sector is underway. To accelerate the development, strategies for the deployment of charging infrastructure are crucial. The absence of public charging infrastructure is a current barrier to the adoption of heavy-duty electric vehicles (HDEVs). As a result, the development of charging infrastructure is a relevant topic to investigate.

An additional consideration is the different technologies that have entered the market of charging infrastructure. As the technologies obtain different characteristics, there are numerous factors to consider when deploying charging infrastructure. The aim of this thesis is to evaluate charging infrastructure for heavy-duty electric vehicles, where the scope is defined to include the three charging technologies; DC-fast charging, DC-fast charging with external battery, and battery swapping. The thesis includes the perspectives of economic, technical, and environmental factors. The purpose of the thesis is to contribute to the decision of which strategy to adopt when deploying charging infrastructure in a Swedish context.

The methodology for this thesis comprises an explorative approach that includes both quantitative and qualitative considerations, to assess the defined research questions. The explorative approach was chosen for the investigation of the charging technologies, enabling flexibility and iterative revisions. To evaluate the charging technologies, six relevant criteria are determined. The criteria are chosen by their relevance for the development of charging infrastructure, and the evaluation will be approached from a quantitative and theoretical perspective. The criteria that are important to consider when developing charging infrastructure are in this thesis concluded to be; investment, charging time, yearly electricity cost, climate impact, scalability, and, technological lock-in. These criteria cover economic, technical, and environmental aspects. The quantitative approach is adopted for four out of six criteria; investment, charging time, yearly electricity cost, and climate impact. The approach involved a systematic collection of data, specific to each criterion, where the purpose was to obtain valid data on which the calculations are based. The results are being validated and iterated as necessary. The two remaining criteria, scalability, and technological lock-in, are considered from a theoretical perspective, where the literature study acts as the ground for the evaluation. To complement the literature study, two interviews and one workshop is conducted. This comprises the result for the un-quantifiable criteria.

The results of the thesis are that DC-fast charging has beneficial investment costs but faces challenges related to load management, high electricity costs, and potentially larger climate impact than the other technologies. However, DC-fast charging is considered more mature than the other two technologies. DC-fast charging with external battery involves high investment costs due to the battery energy storage system. However, with current conditions, the pay-back time is not beneficial. Although, the results imply that with higher electricity costs or reduced investment costs for external battery, the solution will be more competitive. The external battery enables load management, resulting in lower yearly electricity costs and climate impact. It overcomes limitations related to grid capacity. Battery swapping offers quick recharge time and load management capabilities, reducing energy costs and emissions. However, it requires extensive collaboration, business model transformation, and policy changes in Sweden. Compatibility between vehicles, swapping stations, and batteries is crucial for adoption. Policies and standards are shown to play an important role when referring to the deployment of charging infrastructure, where the implementation of regulations could help accelerate the adoption in Sweden.

The contributions of this study lie in the comprehensive evaluation of the charging technologies considering the six criteria. Furthermore, the study fills a gap in the literature by comparing different charging technologies based on the identified criteria and addressing the research questions. It highlights the challenges and advantages of DC-fast charging, DC-fast charging with external battery, and battery swapping, specifically in the context of Sweden.

Keywords: Charging infrastructure, HDEVs, DC-fast charging, Battery Energy Storage System, Battery swapping, Grid capacity, Electrification

Sammanfattning

Transportsektorn är i hög grad beroende av fossila bränslen och står just nu för en betydande andel av de globala utsläppen av växthusgaser. Elektrifiering av transportsektorn är en strategi som har implementerats på EU och nationell nivå för att hantera dessa problem. Därför sker övergången till en elektrifierad transportsektor just nu. Avsaknaden av offentlig laddningsinfrastruktur är för nuvarande ett hinder för att införa tunga elfordon i ett svenskt kontext. Detta leder till att utveckling av laddningsinfrastruktur är ett relevant ämne att undersöka.

Det finns olika tekniker för laddningsinfrastruktur, och marknaden för laddningsinfrastruktur utvecklas hela tiden. Eftersom teknikerna besitter olika egenskaper finns det många faktorer att ta hänsyn till vid utbyggnad av laddinfrastruktur. Syftet med denna uppsats är att utvärdera laddningsinfrastruktur för tunga elfordon, där omfattningen definieras till att inkludera de tre laddningsteknikerna; DC-snabbladdning, DC-snabbladdning med externt batteri och battery swapping. Uppsatsen inkluderar perspektiven för ekonomiska, tekniska och miljömässiga faktorer. Syftet med uppsatsen är att bidra till beslutet om vilken strategi som ska användas vid utbyggnad av laddinfrastruktur i en svensk kontext.

Metoden för denna uppsats omfattar ett explorativt tillvägagångssätt som inkluderar både kvantitativa och kvalitativa överväganden, för att bedöma de definierade forskningsfrågorna. Det explorativa tillvägagångssättet valdes för undersökningen av laddningsteknikerna, vilket möjliggör flexibilitet och iterativa revideringar under arbetets gång. För att utvärdera laddningsteknikerna så fastställs sex kriterier. Kriterierna väljs utifrån deras relevans för utvecklingen av laddningsinfrastruktur och för att beröra ett ekonomisk, tekniskt och miljömässigt perspektiv, utvärderingen kommer att genomföras från ett kvantitativt och kvalitativt perspektiv. De kriterier som är viktiga att beakta vid utveckling av laddinfraladdinfrastruktur är i detta arbete: investering, laddningstid, årlig elkostnad, klimatpåverkan, skalbarhet och teknologisk inlåsning. Dessa kriterier omfattar ekonomiska, tekniska och miljömässiga aspekter. Den kvantitativa metoden används för fyra av sex kriterier: investering, laddningstid, årlig elkostnad och klimatpåverkan. Tillvägagångssättet innebar en systematisk insamling av data, specifikt för varje kriterium, där syftet var att få fram giltiga data som beräkningarna baseras på. Resultaten valideras och itereras vid behov. De två återstående kriterierna, skalbarhet och teknologisk inlåsning, betraktas ur ett teoretiskt perspektiv, där litteraturstudien fungerar som en grund för utvärderingen. För att komplettera litteraturstudien har två intervjuer och en workshop genomförts. Detta utgör resultatet för de icke-kvantifierbara kriterierna.

Resultaten av arbetet ger att DC-snabbladdning har låga investeringskostnader men står inför utmaningar relaterade till lasthantering, höga elkostnader och potentiellt större klimatpåverkan än de andra teknikerna. DC-snabbladdning anses dock vara mer mogen än de andra två teknikerna i ett svenskt konext. DC-snabbladdning med externt batteri innebär höga investeringskostnader på grund av investeringskostnaden för teknikens energilagringssystem. Med nuvarande förhållanden är återbetalningstiden inte fördelaktig. Känslighetsanalyser visar på att högre elkostnader eller minskade investeringskostnader för externt batteri kommer bidra till att lösningen är mer konkurrenskraftig. Det externa batteriet möjliggör laststyrning, vilket resulterar i lägre årliga elkostnader och lägre klimatpåverkan. Samtidigt övervinns tekniken begränsningar relaterade till nätkapacitet. Battery swapping erbjuder snabb laddningstid och lasthanteringsfunktioner, vilket minskar energikostnaderna och utsläppen. Det kräver dock omfattande samarbete, omvandling av affärsmodeller och policyförändringar i Sverige. Kompatibilitet mellan fordon, bytesstationer och batterier är avgörande för införandet av battery swapping. Policyer och standarder har visat sig spela en viktig roll när det gäller utbyggnaden av laddinfrastruktur, där implementering av regelverk kan bidra till att påskynda införandet i Sverige. Bidraget från denna studie ligger i den omfattande utvärderingen av laddningsteknikerna med hänsyn till de sex kriterierna. Dessutom fyller studien en lucka i litteraturen genom att jämföra olika laddningstekniker baserat på de identifierade kriterierna och genom att besvara forskningsfrågorna. Den belyser utmaningar och fördelar med DC-snabbladdning, DC-snabbladdning med externt batteri och battery swapping, särskilt i Sverige.

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Erica Dellien & Wilma Gustafsson
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Terminology

Specific and technical terms frequently used in the thesis are presented below in alphabetical order:

AET Autonomous Electric Truck

BESS Battery Energy Storage System

CET Connected Electric Truck

DC Direct Current

ESS Energy Storage System

EV Electric Vehicle

HDEV Heavy Duty Electric Vehicle

HDV Heavy Duty Vehicle

ICE Internal Combustion Engine

MCA Multi-criteria analysis or Multi-criteria decision analysis

OEM Original equipment manufacturer

SOC State of Charge

UR Utilization rate

VRFB Vanadium redox flow battery

V2G Vehicle-to-grid

ROI Return on investment

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1 Introduction

The introduction introduces a background to the thesis together with the fundamental ideas such as aims and research questions. Furthermore, an explanation of the collaboration with the case company and a description of delimitations are necessary for the study.

1.1 Background

The transport sector is currently the sector with the highest reliance on fossil fuels and could in 2021 account for about 37% of the total global CO₂eq emissions (IEA 2023). The freight industry presents 12% of all CO₂eq emissions in the entire U.S. economy (Vanek 2019). Road freight transport is dominated by internal combustion engine (ICE) vehicles which state a problem for global decarbonization. Additionally, greenhouse gases from road freight are expected to increase by 56% to 2025 compared to 2015 (Mulholland et al. 2018). Leading to rising interest in the electrification of freight industry vehicles (Palencia et al. 2017), where electric vehicles (EVs) can be a strategy to mitigate environmental air pollution. Electrification of the transportation sector is one of many necessary strategies to meet the targets of the Paris Agreement. To decrease carbon emissions, electric vehicles and renewable energy sources can be seen as a strategy (Richardson 2013). Three main opportunities are identified for the transition of an electrified heavy-duty freight in Sweden; the demand for cooperation when deploying charging infrastructure, reinforcement of the power grid, and long-term and predictable policies (Fossilfritt Sverige 2022).

International Energy Agency (2023) presents the growing market for Heavy-duty electric vehicles (HDEVs), where more than 60 models for HDEVs were introduced to the global market in 2022. This resulted in an increasing number of the total available models to over 800 deriving from different original equipment manufacturers (OEMs). As the HDEVs market is nascent there is an opportunity for the market to provide different solutions for both the vehicles and the charging systems. The increase of models for EVs in the market signifies that there is confidence by the OEMs that the supply in the market will rise. For now, a vast majority of produced and sold HDEVs are from China, a forerunner for the adoption of HDEVs (ibid.).

Transportation of goods is an essential part of the global economy and other social factors, leading to a contributory motivation for the electrification of the transport sector. Large transport buyers and haulage companies with ambitious sustainability objectives are the driving force behind the development of electrified freight in the near future (Energiforsk 2022). In 2022, around 320 000 HDEVs were active on the roads which is evidence of progress for the transitioning (International Energy Agency 2023). EVs often have a shorter range than traditional vehicles, making extensive charging infrastructure a prerequisite for electrification. Charging infrastructure is seen to be a success factor for electric vehicles to achieve sufficient performance (Energiforsk 2022).

Charging EVs face challenges that traditional ICE vehicles avoid. This is because charging EVs relies on real-time capacity in the power grid (Arora et al. 2021b). In comparison to fueling ICE vehicles, fossil fuel can be stored in tanks and thereby be regulated easier. For electricity, this kind of storage is more complex. The electrical power supply is managed in real-time and charging EVs create a momentary imbalance in the grid requiring the supplier to increase production (ibid.). However, it is crucial to consider that a large EV charging load or a large number of small EV charging loads will affect grid stability. Additionally, policies and standards play an essential role when adopting charging infrastructure (Borlaug et al. 2022). Furthermore, there is a need for research and investment in technology development (ibid.).

To address these problems this thesis will consider three different charging technologies: DC-fast charging, DC-fast charging with an external battery, and battery swapping. These technologies will be assessed from important aspects when developing a strategy and deploying charging infrastructure. The aspects will be approached both with quantitative and qualitative measures. There are studies covering the emerging technologies of charging infrastructure and the future of electric vehicles. However, to the author's knowledge, there are no studies comparing the charging technologies from a broad-based perspective in a Swedish context. The early stage of electrification of the transportation sector motivates the study. Additionally, the thesis will complement already existing knowledge in the area.

1.2 Aim and purpose

The aim of the thesis is to investigate different charging techniques as a strategy for the development of charging infrastructure within heavy-duty electric vehicles in Sweden. The thesis will identify factors that are important for charging infrastructure. From the factors of the charging technologies; DC-fast charging, DC-fast charging with external battery and battery swapping will be assessed and compared. The purpose of this study is to investigate potential strategies for charging infrastructure at a public charging station of HDEV regarding economic, technical, and environmental factors.

1.3 Research questions & problem description

The charging infrastructure for HDEVs in a general context is still in the developing phase. One barrier to the deployment of charging infrastructure can be to define which charging technologies to adopt. There are different options for charging technologies, therefore it is important to examine the individual characteristics. The research questions have been defined to cover an economic, technical, and environmental perspective in a Swedish context. To fulfill the aim of the thesis, the following research questions have been defined:

- RQ1: What factors are relevant for the development of charging infrastructure, when considering economical, technical, and environmental aspects?
- RQ2: How do the charging technologies perform against the defined factors?
- RQ3: What are the relative advantages and limitations of the different charging technologies?

1.4 Delimitations

Despite the system overview of electrified heavy-duty vehicles, the study has several delimitations. The thesis is limited to investigating charging technologies for heavy electric vehicles powered by batteries exclusively, taking into account the activities of the case company. As for now, battery-powered EVs are the most common and mature technology in the market (Arora et al. 2021b). Therefore, of relevance to include in this study. The thesis will cover three different fleets, which are the autonomous electric truck (AET) fleet, the case company's internal connected electric truck (CET) fleet, and the external customer fleet. Thus, the factors and charging technologies are specifically investigated and with various conditions. With this noted, there could be other criteria or technologies that would be interesting for further investigation. To delimit the scope the thesis is chosen to investigate the vehicle fleets concerning three charging technologies; DC-fast charging, DC-fast charging with external battery storage, and battery swapping. The analysis will be performed for the scenario in which the charging technologies are applied to a charging site where all three vehicle fleets operate. There are different variations of charging sites as; depot charging, semi-public, and public charging sites (Energiforsk 2022). The charging technologies investigated in this thesis are assumed to operate at a public charging site, with fast charging demand.

The following delimitations have been defined, to narrow the scope further:

- A case study is set to be the foundation of the model to provide the same circumstances for each scenario.
- The context of Sweden and electricity bidding area SE3 are used.
- The evaluation is only considering heavy-duty electric vehicles that carry goods. A vehicle is considered heavy if the gross vehicle weight rating is higher than 3,5 tonne (ibid.), which is used as a definition of HDEVs for this thesis.
- When referring to a future perspective a scenario around the year 2030 is assumed.
- The maintenance cost, service cost, software cost, and insurance cost for the charging technologies is not considered in this study.

An important part of the future of EVs is the possibility to supply power back to the grid to act as an energy service (Das et al. 2020). Despite this, the thesis is delimited to not address that area for the future of charging infrastructure for HDEV. The possibility of using batteries as an energy service is delimited from this study as its main scope is considering the charging infrastructure. At the same time, excluding the calculations and aspects needed will contribute to a more manageable scope. Further, an interesting perspective that would possibly bring revenues is how a charging site with battery energy storage could be an actor in the flexibility market, however, this study does not perform any calculations on how this would be executed.

1.5 Collaboration

The thesis has been conducted in collaboration together with a case company that will not be announced by name, and therefore referred to as "case company". The case company provides autonomous and electric transport services. Apart from trucks, the service includes a software solution that has its goal to provide an end-to-end plan for how to electrify operations with minimized cost and maximized environmental benefit. The case company is also providing charging solutions and is facing above mentioned difficulties with the design of the charging infrastructure. Their charging stations will provide charging solutions for both internal HDEVs and external customers.

1.6 Structure of the study

The thesis structure is presented in Figure 1.1. *Section 1* includes the introduction to the thesis, comprising an overview of the background referring to the problem, an exploration of the significance and relevance of the topic, and the evaluation. Furthermore, the thesis aim, purpose, and research questions are presented together with the delimitations determined for the thesis. *Section 2* provides a theoretical framework that considers the Swedish energy landscape, the power system, and environmental impact. Moreover, heavy electric freight and charging technologies are addressed in the theoretical framework.

The outline of the study is presented in *section 3*, addressing the criteria identification, interviews, workshop, and multi-criteria analysis, together with details about the specific case study used for the evaluation. *Section 4* addresses the determination, and the performance of calculations for each of the criterion. The result and analysis are presented in *section 5*, where the sensitivity analysis is incorporated. Discussion about the findings is presented in *section 6*, together with discussions about the methodology in terms of reliability, validation, and generalizability. Finally, the conclusions and future work recommendations are presented in *section 7*.

1. Introduction	Background Aim, purpose and delimitations
2. Theoretical framework	Collection of relevant theory
3. Methodology	Case study Description of methodology and method
4. Criteria for assessing charging technology	Performing assessments for criteria Calculations and summary
5. Results and analysis	Assessment and literature study results
6. Discussion	Discussion of findings and methodological critique
7. Conclusion	Conclusion and future work

Figure 1.1: Presents a comprehensive outline of the process and contents of the study.

2 Theoretical framework

The theoretical background presents an overview of relevant theory on the topic of the thesis. The chapter introduces the Swedish energy landscape, the electrical power grid, and how it relates to an expansion of the current state of electric freight, and opportunities and obstacles with the development of charging infrastructure for HDEVs. Followed by, a theoretical presentation of the three charging technologies that have a significant role in the thesis and later will be a part of the evaluation. Lastly, the role of policies and standards is presented.

2.1 The Swedish energy landscape

The Swedish energy landscape uses a mix of energy sources. Sweden utilizes domestic renewable sources such as hydro, wind, solar, and biofuels. Sweden also imports nuclear fuels, biofuels, and fossil fuels (Swedish Energy Agency 2023). Electricity generation in Sweden is mainly based on energy-sources such as hydropower and nuclear power. Wind power is an energy source that significantly has increased over the last ten years (ibid.). In the Swedish transport sector, 0,5 TWh of electricity was used in 2020. The use of electricity as an energy source for road transport has significantly increased due to electrification (ibid.).

Historically the electricity prices in Sweden have been stable, however recently the prices have increased due to increasing fuel prices and energy taxes (ibid.). Additionally, introducing more sources of wind and solar into the system results in new demands on flexibility between generation and consumption (ibid.). Another arising demand is two-way flows in the grid, where consumers also can produce electricity. To increase sustainability, competitiveness, and security of supply, Sweden has energy policies and targets (ibid.). Yet, not achieved targets are 50 % more efficient energy consumption by 2030 compared to 2005 and 100 % renewable electricity production by 2040 (ibid.).

Responsible to ensure that Sweden's transmission system for electricity is safe, environmentally sound, and cost-effective - today and in the future is the Swedish authority Svenska Kraftnät (SVK) (Svenska Kraftnät 2023). The power system consists of a part where physical transmission takes place and a financial part where electricity trade is facilitated (Svenska Kraftnät 2021b). The electricity trade is facilitated on the stock market, where a balance between supply and demand is established (Energimarknadsinspektionen 2021b). When sellers and buyers bid anonymously, a system price for hourly spot prices, in the individual bid areas is determined. The price relates to the price to produce the last entity of electricity that is needed to meet the demand. This type of pricing is called marginal pricing. All sellers and buyers supply and demand are aggregated into a supply curve and a demand curve (ibid.). The production facilities with the lowest variable cost are initiated first, and depending on the demand more expensive facilities are initiated as well. Wind power and hydropower have low variable costs, while facilities using raw materials such as coal or oil have high variable costs (ibid.). In Figure 2.1 the marginal pricing curve can be seen, visualizing that the larger demand for power the more production facilities need to be introduced resulting in a system price established at the cost for the last produced kWh. In Figure 2.1 it can also be seen that wind and hydropower are less cost-intensive than energy types produced from fossil fuels.

Demand is an important factor affecting the energy price. Therefore, a flexible demand can decrease cost peaks (Energimarknadsinspektionen 2021a). Increased reliance on electricity in the industry and transportation sectors is expected to have an interplay on electricity prices in the long term. Also, other external factors affect the supply (Energiföretagen Sverige 2023). During dry periods, the amount of water in the hydro-power water reserves is reduced, which leads to higher prices. However low raw material costs and a larger amount of renewable energy sources in the energy mix reduce the prices (ibid.). The pricing in the electricity trading market is very reliant on numerous factors such as supply, demand, and external factors.

As previously mentioned, the pricing varies depending on numerous factors, there is also a large variance in the prices. The demand varies over the day but it generally peaks around 7 A.M and 5 P.M During nights, evenings, and weekends the prices are lower since industry and private users have a using pattern characterized by a lower demand (Djerf 2022). In Figure 2.1 it is visible that the prices increase significantly while the demand increase, explaining why prices in the electricity trade market vary.

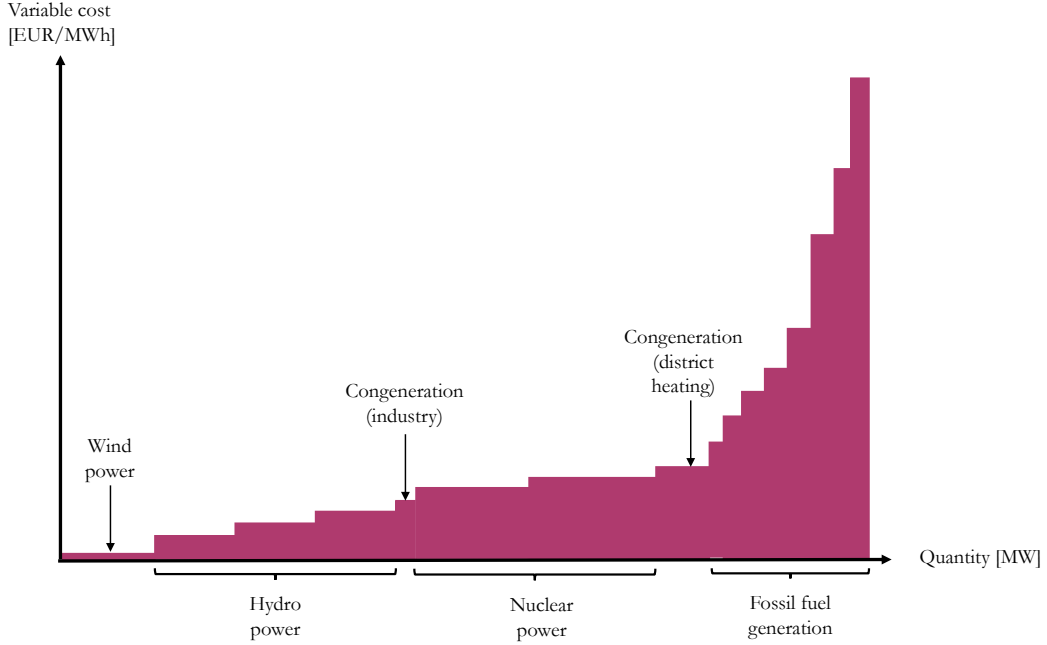


Figure 2.1: Marginal pricing curve for electricity trade.

2.1.1 Balance and capacity in Swedish power system

SVK has assigned responsibility to maintain the balance between supply and demand in every moment (Svenska Kraftnät 2023). In Sweden today a large share of the energy generation takes place in the northern parts, however, the majority of the use takes place in the southern parts. As a result, there is a need to transport electricity over long distances in the transmission grid (ibid.). While the population increase in numbers and new needs for electricity in industry and transportation sectors arise, lack of capacity limits that development (Axberg et al. 2020). The grid is facing extensive challenges concerning capacity in connection to the increased demand that electrification of the transport sector requires (ibid.). There is a rapidly increasing demand, however, the traditional solution to limitations in capacity is to expand the grid, which can take between three to five years for the regional grid and ten to 15 years for the transmission grid (ibid.). This is because of long authorization processes and the involvement of many actors. To be able to meet the emerging capacity need in the short term, there is a need for other actions. Such as creating flexible resources, in terms of demand, supply, and storage (ibid.). For the transport sector, it is crucial to develop possibilities for the charging to be conducted flexibly. In Stockholm currently, there is an acute shortage in capacity, due to the fast growth and increased load demand (ibid.). Other regions that are limited by capacity or are at risk to be so are southwest of Skåne, Mälardalen, Uppsala, and Gothenburg (Wiesner et al. 2019). The limitations in capacity have resulted in a hinder for company establishments.

Electrification of heavy transports will be a bigger challenge than passenger EV, due to the high charging power (Lidström et al. 2022). A risk is if the challenges with grid capacity limit the development of required charging infrastructure. The demand for fast charging stations is a rising issue and a crucial enabler for the electrification of the transport sector (X. Liu et al. 2021). This requires a stable reliable power supply and sufficient capacity. Those requirements are challenges in the power system. The high power charging demand that arises if electrification takes place at a large scale may require large investments in infrastructure for transmission to meet the required capacity (ibid.).

Additionally, the increase of unpredictable intermittent power sources, such as wind and solar power, creates difficulties in providing a secure power supply at all times (ibid.). To meet challenges with power supply, energy storage solutions such as energy battery storage can be helpful. Another important factor to handle the challenges with large-scale electrification of the transport sector is to have efficient load management (ibid.). Meaning that the management and timing distribution of load from EV charging can reduce peak demand.

To maintain the balance between the production and demand in the power system, Svenska Kraftnät has introduced the concept of ancillary services (Svenska kraftnät 2021a). There are different types of ancillary services divided into Fast Frequency Reserve, Frequency Containment Reserve, and Frequency Restoration Reserve (Svenska kraftnät 2023). There are varying requirements for the ancillary services regarding volume, active time, and perseverance. The services are voluntary but could become an additional source of revenue for actors that have possibilities for energy storage.

Some of the services are managing frequency maintenance, where these ancillary services are required they grow rapidly in cost and volume (Svenska kraftnät 2021a). One of the ancillary services that deal with frequency maintenance is named Frequency Containment Reserve (FCR) (Svenska kraftnät 2021b). The concept of ancillary services not only contributes to a more balanced power system but also enables the opportunity to increase the number of renewable energy sources in the power system. This refers to the situation when balancing supply and demand in real-time and therefore can support intermittent power sources. Hence, renewable energy sources are not reliant and will be dependent on weather circumstances, where the ancillary services will help and balance the power system when needed. Svenska kraftnät (ibid.) emphasizes that attracting new actors and expanding the ancillary services is a prerequisite for ensuring sufficient supply. Svenska kraftnät (2021a) argues that ancillary services could be both a source of revenue and contribute to the energy transition which are two reasons why actors would want to use the ancillary services.

2.1.2 Cost structure for electricity purchase

Costs for the use of electricity for enterprises are divided into two parts. One part concerns the grid connection and another part for electricity trade (Konsumenternas energimarknadsbyrå 2022). In the electricity trade costs, electricity generation, electricity certificates, and VAT are included (ibid.). Grid costs consist of both variable and fixed costs, such as subscription costs and transmission costs (ibid.). The grid owners have a local monopoly for transmission meaning that a customer themselves cannot choose the grid provider. However, the electricity trade is an open market and customers are free to choose suppliers (ibid.).

The electricity trade costs differ depending on supply and demand as presented in section 2.1. Grid costs, on the other hand, increase depending on the installed peak capacity and the share of energy that is used during high load periods in the grid (Vattenfall 2023b).

2.1.3 Climate impact from electricity generation

The result from a scientific article by Sen et al. (2017) shows that HDEV accounts for a lower amount of greenhouse gases than other trucks. Noteworthy, is that a considerable amount of the emissions that the HDEV is accountable for are related to electricity production (ibid.). Given that, the environmental impact of electricity generation is an important factor affecting the environmental impact of HDEV. Analyzing the environmental impact of electricity generation differs a lot depending on which approach is applied (Gode et al. 2009). Additionally, the Swedish electricity system is closely connected to the Nordic countries' electricity markets, making it accurate to include the Nordic or European electricity market, instead of solely analyzing the Swedish energy system (ibid.).

When analyzing emissions from electricity different approaches can be used. The approaches can give results differing in a factor of 100, therefore it is important to apply an approach that mirrors the case investigated (ibid.). A marginal approach is suitable to apply when assessing changes in electricity use. It refers to the energy source on the margin and accounts for emissions from that source. Based on historical data the energy generation on the marginal is most frequently coal condensation when emissions for environmental accounting are calculated in the Nordic electricity mix (ibid.). However, in the future natural gas will be more accurate (ibid.). Another applicable approach for CO₂eq accounting is the residual mix where the mean value of emissions is applied rather than the marginal value (ibid.). From this result no difference is given depending on what time or day the energy is used since it applies a mean value for emissions. This approach is not suitable when assessing changes in electricity use since a change in use actually results in changes in emissions from the marginal energy source rather than from average emission factors (ibid.).

In the Nordic energy system, power generation can be divided into base power, regulating power, and

intermittent power (Gode et al. 2009). Base power in the Nordic electricity system is mainly nuclear power, hydropower, and fuel-based electricity generation. Hydropower is the main source of regulating power. Given the principle of marginal pricing, supply, and demand, the most cost-efficient generation facilities are prioritized for generation. A marginal pricing approach should be used when changes in electricity use are analyzed. This since a decrease in electricity use would result in the least cost-efficient generation facilities being shut off first and that facility's emissions are the ones that are saved. (ibid.).

2.2 Heavy electric freight

Freight is vital for the transportation of goods and for the global economy. In Sweden, heavy-duty vehicles correspond to more than a quarter of the total amount of freight transported (Fossilfritt Sverige 2020). For the transport sector to move towards a more sustainable future, alternative technologies are explored to transition from a fossil fuel-dependent sector. Actively driving this development, with a new transport system, such as electrified vehicles, can benefit both the environment and society as a whole. The market for heavy-duty electric vehicles is nascent and the technology is emerging (Sen et al. 2017). As a result, the development is contributing to changing circumstances for specifically heavy-duty freight. Features such as lowered energy costs, improved efficiency, and common public acceptance make electric trucks a highly competitive technology for the future of the transportation industry (Strategy& 2022). Energiforsk (2022) proposes a scenario for the market of electric heavy freight, where HDEV is expected to cover 30% - 60% of the total sold new vehicles for 2030. This estimate, and future scenarios, require the deployment of charging infrastructure and grid reinforcement (ibid.). Although electric vehicles are one of many emerging technologies for a more sustainable transportation sector they can be seen as a favorable alternative. A study by Sen et al. (2017) analyzed and compared alternative fuel-powered HDV, which involved traditional diesel, bio-diesel, compressed natural gas, hybrid, and lastly HDEV. The comparison analyzed life cycle cost and environmental emissions. The result from the comparison showed that HDEV outperforms all other types of trucks, in terms of achieving the lowest life cycle cost and emitting the least amount of greenhouse gases compared to the investigated alternatives. The implications include that HDEVs can be a promising alternative for sustainable transportation and for minimizing air pollution (ibid.). This supports the fact that electric freight is vital for the future of the transportation sector.

Freight transportation can be divided into local, regional, and long-distance. The varying distances for freight transport contribute to different conditions for electrifying freight transport (Nåbo et al. 2023). Figure 2.2 presents the number of trucks responsible for the distances local, regional, and long-distance in Sweden. Where the transportation of shorter distances is considered easier to electrify than those who run long-distance. Trucks used for shorter distances and local transportation retain the lowest demand for battery capacity, thus the shorter distances (Energiforsk 2022). Correspondingly, due to the shorter range of distance, it is easier to provide and control charging possibilities during the routes. Depot charging stations are suitable for transportation of shorter distances (ibid.). Depot charging refers to the charging that is conducted in a depot station where the vehicle prepares for the next route (Nåbo et al. 2023). For local transportation, private charging infrastructure may be sufficient. Compared to regional transport, long-distance transport can not only rely on depot charging stations but requires public charging infrastructure. The increase in long-distance transportation with HDEV will require public chargers (International Energy Agency 2022). This puts pressure on charging facilities along the route, where charging should be completed as quickly as possible (Nåbo et al. 2023).

Figure 2.2 shows the distribution of heavy freight in Sweden. The statistics are solely covering Swedish vehicles in 2021. Local transportation refers to national road transport up to 149 km, regional transportation refers to the interval 150 - 299 km and long-distance transportation refers to all national road transportation longer than 300 km. Noticeable is that a majority of heavy freight in Sweden corresponds to local and regional distances, and only a fraction corresponds to long-distance freight. This can be seen as an advantage for the electrification of Sweden's heavy freight due to the distribution of transportation distances. Fossilfritt Sverige (2020) emphasizes that electrification of distances up to 300 km will be conducted, which translates to a large amount of heavy freight.

The adoption of electrical vehicles varies around the world, and China is considered a forerunner in the transition. Sweden-China Bridge is a project with several purposes, for example, to share knowledge and academic collaboration between universities from Sweden and China (J. L. Liu et al. 2021). Furthermore,

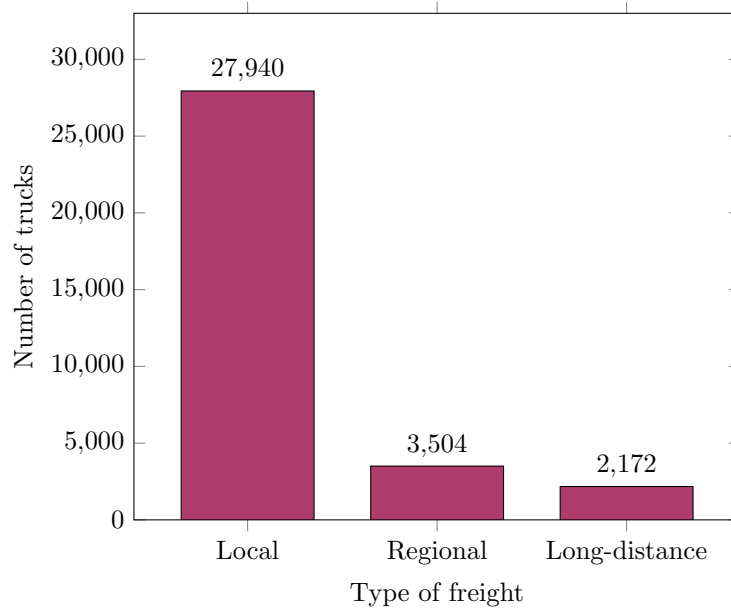


Figure 2.2: Swedish freight transportation divided into local, regional, and long-distance (Traf.se 2021).

the project aims to explore electric vehicles and different technologies for charging infrastructure with the intention to gain knowledge from already implemented strategies in China. The transition towards an electrified transportation sector began early and the result has already proven successful in different parts of China. By 2020 the city of Shenzhen adopted the transition to having a 100% electrified fleet of buses and taxis, likewise a prominent number of trucks (J. L. Liu et al. 2021). China has been an early adopter of electric vehicles in different aspects. Kittner et al. (2019) writes that in 2019 China was accountable for 40% of global investments in EVs, and was a strong actor considering remaining the role of being a big investor in the technology.

2.2.1 Charging heavy-duty electric vehicles

The transition to an electrified transportation sector is highly dependent on sufficient charging infrastructure. Parallel with rising incitements for actors to shift to electric vehicles there is a rising demand for charging possibilities to ensure expected transportation distances and routes. The European Automobile Manufacturers' Association (ACEA), has estimated the demand for charging points for 2025 as a result of the increase of HDEVs on European roads. ACEA estimates that the required demand consists of 24 000 DC charging points with a capacity of less than 100 kW, 11 000 DC charging points with 350 kW, and 2 000 DC charging points with at least 500 kW needed for the year 2025 (ACEA 2020).

One identified challenge associated with the transition is the concerns regarding the driving distances possible for battery-equipped vehicles and as a consequence the availability of charging infrastructure, to ensure sufficient charging possibilities (Borlaug et al. 2022). Local and regional transportation often have scheduled routes with shorter distances which implies that the charging can be planned more efficiently. Often the charging can be completed when the vehicle is unloading- or loading goods, or perhaps standing still in a warehouse (Nåbo et al. 2023). Additionally, due to the short distances, it may be sufficient to charge when parked during nighttime (ibid.). As mentioned earlier in section 2.2, long-distance freight requires alternative charging solutions. The charging process presents a significant obstacle to the widespread adoption of electric vehicle fleets. For local and regional freight transportation it may be sufficient with only a few charging stations on site due to the short transportation range. Most of the charging regarding short-distance related transportation will use terminal charging at their own site except for public chargers in some cases (Energiforsk 2022). The cause of this is that transportation is often scheduled to involve short distances and reoccurring routes. The preconditions for long-distance freight are different, which will require charging possibilities along the roads (ibid.). An estimation by Power circle (2022b) proposes that 40% of the charging required for long-distance HDEV will require a semi-public or public charging station. The charging stations will require an installed capacity of 350-750 kW (ibid.). Therefore, there is a need for a charging infrastructure strategy parallel with the transition

to an electrified transportation sector. The possible location of future charging stations can be determined by scanning freight logistics and their routes. Driving patterns in terms of where the freight stops and drives are of importance. Fossilfritt Sverige (2020) proposes that this systematic review of driving patterns will help determine charging points that will be sufficient for the heavy-duty electrical fleet. If locations for charging stations are optimized the research implies that a few charging locations can meet the need of the majority of the routes. (ibid.).

There are three main technologies for charging EVs; conductive charging, inductive charging, and battery swapping. Where conductive charging is the most mature technique (Arora et al. 2021b). Conductive charging requires a physical connection between the charger and EV battery. Inductive charging, on the other hand, does not require physical contact between charger and vehicle (ibid.). This also enables inductive charging while moving. Inductive charging is flexible but charging power levels are lower than conductive charging (ibid.). The low power level makes inductive insufficient for high power demands in heavy-duty EVs. Lastly, battery swapping is a technique where a discharged battery is swapped with a charged battery (ibid.). Section 2.3 will later cover information about conductive charging and battery swapping in greater detail.

Autonomous electric vehicles (AEVs) can contribute to more efficient transport solutions, thus the opportunity to plan the logistics for both charging and parking without concern about breaks for the drivers (Zhang et al. 2022). The charging of AEVs can be processed in an integrated way for determining when and for how long the charging will be conducted.

2.2.2 Charging loads on the electric power grid

One obstacle related to the deployment of charging infrastructure in Sweden is the available capacity in the local power grids (Fossilfritt Sverige 2020). As mentioned in 2.1.1 there are limitations in the grid capacity in Sweden. An increased amount of electric vehicles and their charging patterns contribute to an increased demand for electricity in Sweden. Alternatively, EVs can generate positive effects, as EVs are important to achieve system flexibility for the electricity grid (International Renewable Energy Agency 2017). As a result, the impacts of EVs on the power grid can be both positive and negative, Das et al. (2020) signifies that excessive integration of EVs in the power grid can result in stresses in the power grid such as the load, voltage, and frequency. For instance, HDEVs can require extremely high-power charging stations to ensure fast charging rates (X. Zhu et al. 2023). The integration will thus affect the peak power transmission and demand, at the same time distribution capacity will be an important factor (International Energy Agency 2022). This results in challenges for the power grid, which is important to take into consideration for the deployment of charging infrastructure. As mentioned in 2.2.1 there will be a need for public chargers along the road, to provide sufficient charging possibilities to increase long-distance electric freight. The deployment of charging stations in rural areas and remote locations may contribute to difficulties regarding grid installation (ibid.). Where costly grid upgrades can be a necessity for the deployment.

To face challenges with grid instability as mentioned in chapter 2.1.1, controlled and flexible EV charging is a rising area within industry and academia (Arora et al. 2021b). Smart charging where planning and off-peak charging will help increase flexibility in the power system is a shift required for the electrification transition (International Energy Agency 2022). According to Arora et al. (2021b) controlled charging can be divided into three subcategories; *Indirectly controlled charging*, *Intelligent controlled charging*, and *Multi-staged controlled charging*. Indirectly controlled charging considers user behavior and controls the load by accomplishing load shifts through incentives (ibid.). This way of charging can manage to optimize and control charging time, rate, and duration to balance the power system (International Energy Agency 2022). In an indirect control, this can be by encouraging users to charge during off-peak hours to a reduced price to avoid grid overload. Intelligently controlled charging considers a data-driven approach where data about vehicles, charging stations and grid are interlinked (Arora et al. 2021b). The purpose is to optimize charging efficiency with power and cost as examples of constraints. Finally, multistage hierarchical controlled charging is a priority-based multilevel decision-making tool with an AI-driven algorithm (ibid.). Parameters taken into account are load capacity, battery state of charge, cost, and time of use. With this type of control, EV batteries also play a role as a power source to regulate frequency in the grid (ibid.). This technique is still in the development stage.

A long-term scenario provided by Svenska Kraftnät emphasizes that the future of the Swedish power

system is in need of a more flexible demand (Svenska Kraftnät 2021a). Electricity storage is considered to be an important part of facilitating the energy transition to increase flexibility. It follows that the charging stations can not supply energy as conventional fuel stations can supply fuel to the vehicles. In the charging stations where the electrical power is generated instantly, where variations of the charging procedure will contribute to direct influence on the power grid and its stability (Arora et al. 2021b). Power management or controlled charging of electric vehicles are two alternative strategies to achieve flexible electricity usage (Arora et al. 2021b; Das et al. 2020). It is important to ensure strategic planning of the charging and enable slow charging to minimize the impact on the electrical grid (International Energy Agency 2022). This can involve charging scheduled during off-peak hours and taking advantage of external batteries which can be charged during chosen time periods.

An energy storage system (ESS) is an alternative solution to avoid load shock and enable peak-load shifting (X. Liu et al. 2021). By integrating an ESS with the charging point, the power grid can be balanced and the charging process can be made more flexible. Battery energy storage system is one promising alternative with the aim to balance the power system and manage peak periods (Power circle 2022b). Therefore, the integration of BESS is an important part of the future development of charging infrastructure.

2.3 Charging technologies

This chapter will include a presentation of the theoretical information about the studied charging technologies. There are several technologies for charging both HDEVs and AEVs, but the theoretical information is limited to DC-fast charging, DC-fast charging with an external battery and battery swapping.

2.3.1 DC-fast charging

As mentioned in 2.2.1 there are different technologies for charging heavy-duty electric vehicles, this study will focus on DC charging for the HDEV. Where DC stands for direct current, which is one of the fastest ways to charge an electric vehicle. DC-fast charging is a way of conductive charging. Conductive charging refers to charging technologies that involve a physical connection from the vehicle to a power source through wires and metallic contacts (Arora et al. 2021b). Conductive charging is the most mature charging technology, the simplest and the greatest adopted technology (ibid.). Conductive charging can be further classified into on-board and off-board. The differences are where the rectifier and battery regulation are placed, inside or outside of the vehicle, and the power flow distributed to the vehicle (AC or DC) (A. Ahmad et al. 2018; Khalid et al. 2019; Rivera et al. 2021). For onboarding the rectifier and battery regulation are placed inside the vehicle (Rivera et al. 2021). Commonly, onboard charging is used for slow charging while off-board charging is suitable for fast charging (Khalid et al. 2019). For off-board charging infrastructure, the rectifier and the converter, which converts the AC power from the grid to DC power to the vehicle, are placed at the charging station. This enables a faster way of charging thus the transfer of power is not limited by an onboard charger, hence fast charging. An off-board charger can manage various power levels and is suitable to perform at high power (Arora et al. 2021b). As a result of the earlier mentioned, conductive charging with off-board chargers are the most convenient and efficient charging method for public charging of HDEVs, where fast charging is required.

DC charging system uses a high-voltage DC power supply to rapidly charge the batteries in the vehicles. Unlike traditional AC charging systems, DC-fast charging can provide a high-power charging rate, enabling vehicles to recharge quickly and return to operation. DC-fast charging can provide a high-power charging rate, ranging from 40 kW to 400 kW depending on the type of charger used (ibid.). As DC-fast charging is suitable for HDEV, it is at the same time a favorable charging alternative for public charging stations. As mentioned in 2.2.1 there is a need for semi-public and public charging stations to meet the demand in correlation to an increase of HDEVs in Sweden.

There are different solutions for the design of a DC-charging station, considering different suppliers and selections. This study will consider the DC-charging solution provided by Kempower. The charging solution contains a power unit and a satellite.

The power unit considers a modular fast charging cabinet that can provide up to 600 kW at the charging station (Kempower 2022a). The power unit can be installed together with either satellites or pantographs

(Kempower 2022a). A pantograph is a conductive connection to the vehicle connected from above. However, this study will not discover the pantograph solution further. The power unit uses dynamic power management to ensure that the available charging power is automatically allocated to the connected outputs in response to the needs of the HDEVs. The power unit is designed to be easy to scale when wanting to supply a bigger vehicle fleet, where it is possible to add-on modules to increase the capacity (ibid.). The satellite refers to the cable management solution in this case provided by the supplier Kempower with the two DC charging outlets (Kempower 2022b). The satellite is connected to the power unit to achieve a DC-charging system. The satellite connects with the vehicles with a CCS2 as a connector type. The solution, of the power unit and satellites, can perform multiple outlets and the possibilities for up-scaling, which is favorable for a charging site where it is possible for a change in demand. As conductive DC-fast charging requires a physical connection between the charger connector and the vehicle, it can be considered a limitation of the charging technology. Furthermore, for the charging to be completed the vehicle needs to be parked at the charging station during the charging downtime. As a result, this can be limitations regarding achieving flexible charging patterns or if the vehicles are operating with rigid schedules (Arora et al. 2021b).

The transport sector is exploring various new technologies, one of which is autonomous transportation. One of the key challenges in achieving full autonomy in the transport sector is ensuring that vehicles can be charged without human intervention. This requires the development of appropriate charging infrastructure that can provide autonomous charging solutions for vehicles. The conventional (non-autonomous) DC-fast chargers require a person to insert the connector into the vehicle to start the charging. Autonomous equipment can be added to the DC-fast charging to provide an autonomous charging solution for the vehicles. For instance, a robotic arm that enables cable connection through intelligent communication between the charger and the vehicle, and with smart camera system (Rocsys 2023). The positive result from autonomous charging can be decreased charging downtime, enhanced user experience and safety measures, more effective utilization of charging infrastructure, reduced cable wear, and readiness for autonomous electric vehicles (ibid.). Intelligent communication between the vehicle and the robotic arm is essential to guarantee that the charging process is conducted safely and efficiently. This communication enables the robotic arm to accurately position the connector and ensure that it is securely connected to the HDEVs charging port. Additionally, it allows for real-time monitoring of the charging process, enabling any issues or irregularities to be detected and resolved quickly.

2.3.2 DC-fast charging with external battery

DC-fast charging with an external battery has similar technical properties as DC-fast charging described in section 2.3.1. The distinction of this charging technology is the external battery, which enables energy storage. As mentioned in section 2.2.2 grid-connected energy storage will help achieve system flexibility, which will be a prerequisite for a future scenario of HDEVs in a wider context.

There are different types of energy storage solutions to choose from when implementing ESS in connection to a charging station. Where one promising alternative is the BESS (Lai et al. 2022). Integrating an external battery into the charging station will enable electricity storage at the site. The storage will help reduce the peak demand, where the vehicles can be charged by the battery during peak hours. This is one way to handle the shortage of capacity in the grid as presented in section 2.1. Since the capacity situation in the Stockholm area is acute it can be of necessity if the required capacity is not available.

Different types of batteries can be used for a BESS. Where Redox flow batteries (RFB) are identified as suitable alternatives for grid-connected energy storage possibilities (Alotto et al. 2014). The article written by Alotto et al. (ibid.) includes a comprehensive review of redox flow batteries and provides several reasons for their high potential as energy storage batteries. One specifically emerging technology among the RFBs is the vanadium redox battery (VRFB), which is an adopted technology and is considered a promising alternative (Lourenssen et al. 2019; Alotto et al. 2014). Proven characteristics of the VRFBs are high efficiency, scalability, and flexibility (Alotto et al. 2014).

The autonomous aspect of DC-fast charging with an external battery is considered to be the same as DC-fast charging. Where autonomous equipment in terms of robotic arms is included in the charging technology to achieve autonomous technology.

2.3.3 Battery Swapping

Charging HDEV can be done by battery swapping technology at a battery swapping station. The procedure consists of replacing a used battery that has been consumed below a predetermined charge level in the vehicle with a fully charged battery (F. Ahmad et al. 2020). Where the swapping can be done in a very small amount of time, the swapping time can be compared with the time that conventional vehicles are being refueled. A battery swapping station works efficiently and can operate between 60 - 100 trucks per day (Nåbo et al. 2023). This makes it an interesting charging technology to investigate to achieve an efficient charging network. The short swapping time enables flexible logistics where idle and charging time for the vehicle is minimized. But for the swapping to be completed efficiently, there is a need for fully charged batteries and no queue. There are different forms of battery swapping as a procedure which is dependent on where the battery is positioned in the vehicles. The performance of battery swapping can be done by different placements of the battery. These are sideways swapping, rear swapping, bottom swapping, top swapping (F. Ahmad et al. 2020), and battery placed behind the cab (J. L. Liu et al. 2021; J. L. Liu et al. 2022). Positioning the battery behind the driver cab is for now the most adapted swapping construction in China (J. L. Liu et al. 2021). The placement of the battery makes it easy to remove and replace in a battery swapping station, as it is accessible with or without cargo. In contrast to bottom swapping, where the battery is placed under the chassis. This alternative is not adopted for trucks but is the most commonly used placement for passenger vehicles that are swappable (ibid.). However, a vehicle suitable for battery swapping involves different characteristics compared to a vehicle using cable charging.

Battery swapping relies on comprehensive planning of all necessary requirements for a battery swapping site. Thus, the battery-swapping operation occurs in a short amount of time. The stations will be occupied only for shorter time slots and the sites can be constructed without immense effort (Schmidt 2021). Correspondingly, the swapping time can be less than five minutes which is seen as a considerable benefit for the technology (F. Ahmad et al. 2020). As a result of the short swapping time, allows the battery management to be scheduled which can enable slow charging of the battery. A study by F. Zhu et al. (2023) was done considering battery swapping and fast charging, the result shows that battery swapping enhances more efficient transportation without large grid expansions and infrastructure costs. Additionally, F. Zhu et al. (ibid.) discusses that the main factor for competitiveness for battery swapping is the utilization rate for the battery swapping stations. From a logistic perspective, battery swapping provides a reduced idle time for transportation when the battery is fully swapped compared to waiting times for battery charging (Arora et al. 2021a). This is favorable in terms of the operational processes for the HDEV, where battery swapping can be considered suitable for tight time schedules. According to F. Zhu et al. (2023) battery swapping is the foremost cost-effective charging technology for HDEV when the utilization rate is more than 43%. Battery swapping as charging technology is efficient thus there is a less extensive need for grid expansions or charging equipment costs. The battery load in a battery swapping station can also be applied to manage peaks and fill valleys in demand, in the power grid (Danilovic et al. 2021). A study by Schmidt (2021) shows that battery swapping as charging technology requires less battery capacity concerning the vehicle fleet in total, the reason for this is due to the shared battery packs.

Battery swapping faces new challenges that cable charging overcomes, where designing the business model is one. There are different alternatives for how the business model can be designed, for instance battery subscription and battery as a service. Danilovic et al. (2021) argues that a business model where the vehicle and the battery are separated is a favorable alternative for battery swapping. Correspondingly, this business model could involve an arrangement where the vehicle operators rent the batteries. When separating the purchase of the vehicle from the battery, it is possible to achieve a substantial reduction in the upfront costs (International Energy Agency 2023). An arrangement similarly will enable the flexibility for alternating between short and long distances (Danilovic et al. 2021).

Battery swapping as a charging technology is widely adopted in the Asian region, and in 2020 battery swapping was implemented in the national strategy in China (J. L. Liu et al. 2021). Battery swapping HDEVs is, in China, mainly involved in innovative business models (J. L. Liu et al. 2022). The business model differs from the conventional model in the sense that the truck is bought without a power source and then batteries are rented and battery charging is a service subscription (ibid.). When ownership of the battery and vehicle is separated a battery asset company can handle battery management, data monitoring, safety, residual value, and improved life-cycle performance (ibid.). At the same time, the

technology is still developing and is a quite rare topic in academic papers (Schmidt 2021). Key challenges identified regarding the battery swapping development in China, are safety issues, standards for batteries, and utilization scenarios (J. L. Liu et al. 2021).

For autonomous vehicles, some necessities need to be assured to complete charging through battery swapping. A report by Nåbo et al. (2023) presents that communication, identification, and automation are needed for battery swapping for autonomous vehicles. Scheduling of charging, the ability to be recognized by the station, and the possibility to automatically select the most favorable charging station are all important parameters to review when introducing battery swapping as a solution for heavy-duty AEVs. Arora et al. (2021b) provides an explanation of an autonomous version of a battery swapping station, where robotic arms are included to automate the process. For the battery swapping station to include autonomous equipment implies that it is compatible with an automated vehicle fleet without any personal interaction.

2.4 Policies and Standards for electric freight and charging HDEV

To deploy charging infrastructure in Sweden to a greater extent, policies and standards are needed. The development of electric freight has political support from both Sweden and the EU (Energiforsk 2022). Where policies can help overcome obstacles related to the deployment and help facilitate the implementation of charging infrastructure in Sweden. The policies differ in how they are presented and implemented and can be either economic, regulatory, or informative (Naturvårdsverket 2012). Desirable, is that there is a mix of policies addressing the same area for an efficient implementation. For instance, where informative policies can help achieve acceptance for policies that are administrative or economic (ibid.). Moreover, a variation in policies such as regulations, financial incentives in terms of subsidies, and informative campaigns can help the deployment of charging infrastructure. Where policies can encourage the development of the infrastructure, and standards can contribute to a unified implementation. International Energy Agency (2022) argues that identified obstacles for the development of strategic charging infrastructure are lack of support by the government and inadequate policies. The result of the identified obstacles may contribute to well-deployed infrastructure only in localized areas. Furthermore, it is noticed that policies and regulations aiming for HDEVs tend to be less ambitious than equivalent for light-duty vehicles (ibid.).

The electrification of the transportation sector is influenced by both EU and Swedish legislation (Power circle 2022a). There are different types of regulations and directives that affect the shift to electrification, either directly or indirectly. For example, policies such as carbon taxes or regulations for conventional vehicles will indirectly support the development of electric vehicles. In terms of promoting electrical transportation and charging infrastructure as a way to minimize emissions from transportation. The Global Electric Vehicle Outlook 2022, published by International Energy Agency (2022), demonstrates that Europe is aiming to advance charging infrastructure to meet the growing demand for HDEVs in different areas. The focus rely upon standardization, enhanced charging performance, extensive charging infrastructure in both developed and rural areas, and flexibility regarding the adoption of improved charging technologies (ibid.).

In February 2023, the European Commission shared a revised version of the regulation on CO₂ emission standards for heavy-duty vehicles (European Commission 2023d), which is applicable to Sweden. The previous targets from 2019 have been revised and replaced with a more stringent ambition, as presented in Figure 2.3.

Figure 2.3 presents the targets for the reduction of emissions by years 2030, 2035, and 2040. In contrast to the earlier target for 2030, a decrease of 30%, the new requirements have set a demand of decreasing the emissions by 45%. This indicates a more ambitious target regarding the electrification of the transportation sector. The regulation aims to increase the number of zero-emission vehicles, such as EVs, to substitute conventional vehicles and help accelerate the charging infrastructure to support the shift (ibid.). The policy will help actors investigate alternative fuels, with the aim to lower CO₂ emissions. To support the shift from conventional HDV to HDEV economic policies can support the transition to close the cost difference between the two. In a shorter time frame, there is a need to focus on the infrastructure. The development will require a focus on semi-public and public charging stations in particular, where the greatest demand for charging will be found (Energiforsk 2022; Fossilfritt Sverige 2020). As local and

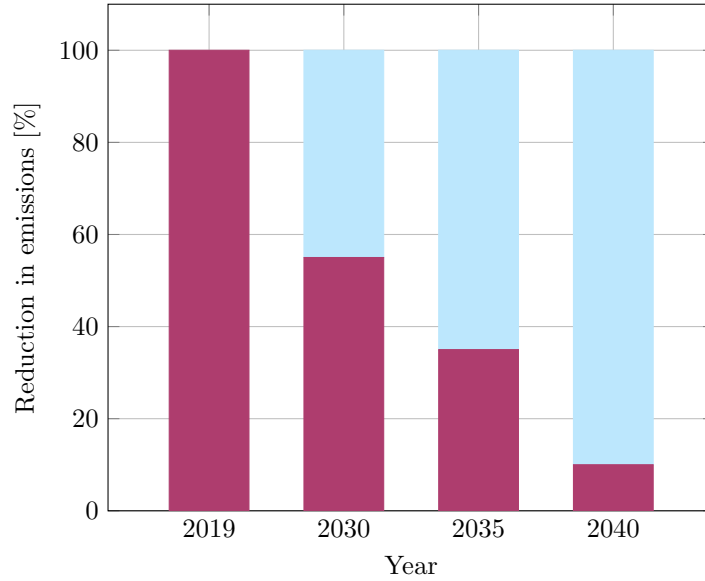


Figure 2.3: Emission reduction for new vehicles according to EU requirements (European Commission 2023d).

regional transportation requires charging at these locations.

Electrification pilots, with the Swedish title *Regionala elektrifieringspiloter*, is a policy by Energimyndigheten in Sweden that provides financial support to cover the total investment cost of the project (Power circle 2022a). The policy can be used for deploying charging infrastructure in Sweden as a regional electrification pilot. The aim of the policy is to accelerate the electrification of heavy-duty vehicles carrying goods and to provide charging solutions for regional transportation (ibid.). To get accepted by Swedish Energy Agency there are requirements in terms of technical aspects and sharing knowledge and learnings from the project. The electrification pilot is one example of how Swedish policies help facilitate the deployment of charging infrastructure for HDEV.

Standards for both electric vehicles and charging infrastructure are prerequisites for successful deployment on a larger scale. At the moment, the standards for charging components vary around the world, as does the level of maturity for the components. To achieve an interoperable way of charging HDEVs, worldwide standards have been established (Arora et al. 2021b). Arora et al. (ibid.) proposes a breakdown of the standards in terms of regulations relating to either (1) the charging components, (2) safety measures, and (3) the grid integration. Similarly, Das et al. (2020) presents the same breakdown for standards related to Evs. As for these standards, they vary among different parts of the world (Arora et al. 2021b). Where some are prominent in either China, the USA, or Europe, which makes the standardization of charging HDEVs separate worldwide.

The plug, or connector, is referring to the connecting handle between the charging component and the vehicle. The design of the connector is one component that often is determined by standards (Das et al. 2020). Table 2.1 presents an overview of identified standards that comprises the connector intentionally used for DC charging. Furthermore, the grid integration standards are including specifications for charging and discharging with the grid (ibid.). The safety standards include specific standards for safety and security (ibid.).

Table 2.1: Overview of different standards for the connectors used for DC-charging (Lidström et al. 2022; Rivera et al. 2021)

Specifications	CCS-1	CCS-2	CHAdeMO
Maximum power	350 kW	350 kW	400 kW
Region	US, South Korea	Europe, Australia	Asia
Area of charging	Semi-fast DC	Semi-fast DC/fast DC	Semi-fast DC/fast DC

Table 2.1 presents the differences in standards from a global perspective, where CCS-2 and type-2 are prominent in Europe. The combined charging system (CCS) is a global system specification that are covering different types of charging standards. The CCS includes a universal solution for single-phase and three-phase AC together with DC high-power charging in the US and Europe, which includes specifications for HDEV (Rivera et al. 2021). The CCS standard comprises two different types: CCS-1 and CCS-2 as mentioned in Table 2.1. Differences between the two types are regarding the plug type, where CCS-2 is designed to suit two types of ports to be connected to both AC and DC power (Lidström et al. 2022). Where CCS2 is a standard used for charging HDEV (ibid.). CHAdeMO has its origin in Japan and is widely adopted in the Asia region (ibid.). In 2020, a new model of CHAdeMO was released to enable a charging power of up to 900 kW and to be suitable for HDEVs (Rivera et al. 2021). According to Rivera et al. (ibid.) the CHAdeMo standard was facing difficulties regarding incompatibilities between vehicles in terms of lack of hardware standards. These problems were recognized and the CCS standard overcame these problems by introducing a universal solution where different types of charging types for various regions are included, where safety measures and authentication are included (ibid.).

As noticed in Table 2.1 there is a unified standard adoption for different regions. A prerequisite for the coupling handle is that neighboring regions adopt the same design when they have combined transport (Nåbo et al. 2023). Where the connectors are an important component to be the same for enabling charging across regions. Whereas, there is not a common adoption of the standards globally. Das et al. (2020) emphasizes that a globally joint approach to the standards would lower the costs and also contribute to a more attractive perception of electrified transportation. Borlaug et al. (2022) signifies that the immature market of HDEVs is one factor that hinders the possibility to determine specific standardizations and requirements for infrastructure and components. Correspondingly, Arora et al. (2021b) emphasizes the importance of standardizations for the specific charging technologies for the cause of maintaining interoperability in a fast-developing market. Where a hinder is when the industry practices advance more quickly than the process of developing and implementing standards and regulations.

J. L. Liu et al. (2021) emphasizes a lack of standards regarding batteries used in Battery Swapping stations. Which is considered hindering in terms of future development and adapting the battery swapping technology in a global context. Standards for the battery size and layout are not considered by any standard, neither are the installation location and interface (ibid.).

3 Methodology

This section will present the chosen methods in consideration of the aim and the research questions of the thesis. Firstly, a presentation of the methodology approach, followed by the methods in greater detail.

3.1 Methodology approach

The thesis has comprised both a quantitative and a qualitative study. A definition of a quantitative study by Patel et al. (2019), is where measurements and calculations of reality are made followed by an association of the result to relevant theory. This study was conducted in accordance with the prescribed approach, as the approach could be iterated when calculating and validating the results. Moreover, to support the quantitative parts, a qualitative study was conducted for factors that are important but not able to be quantified. Figure 3.1 presents an overview of the structure.

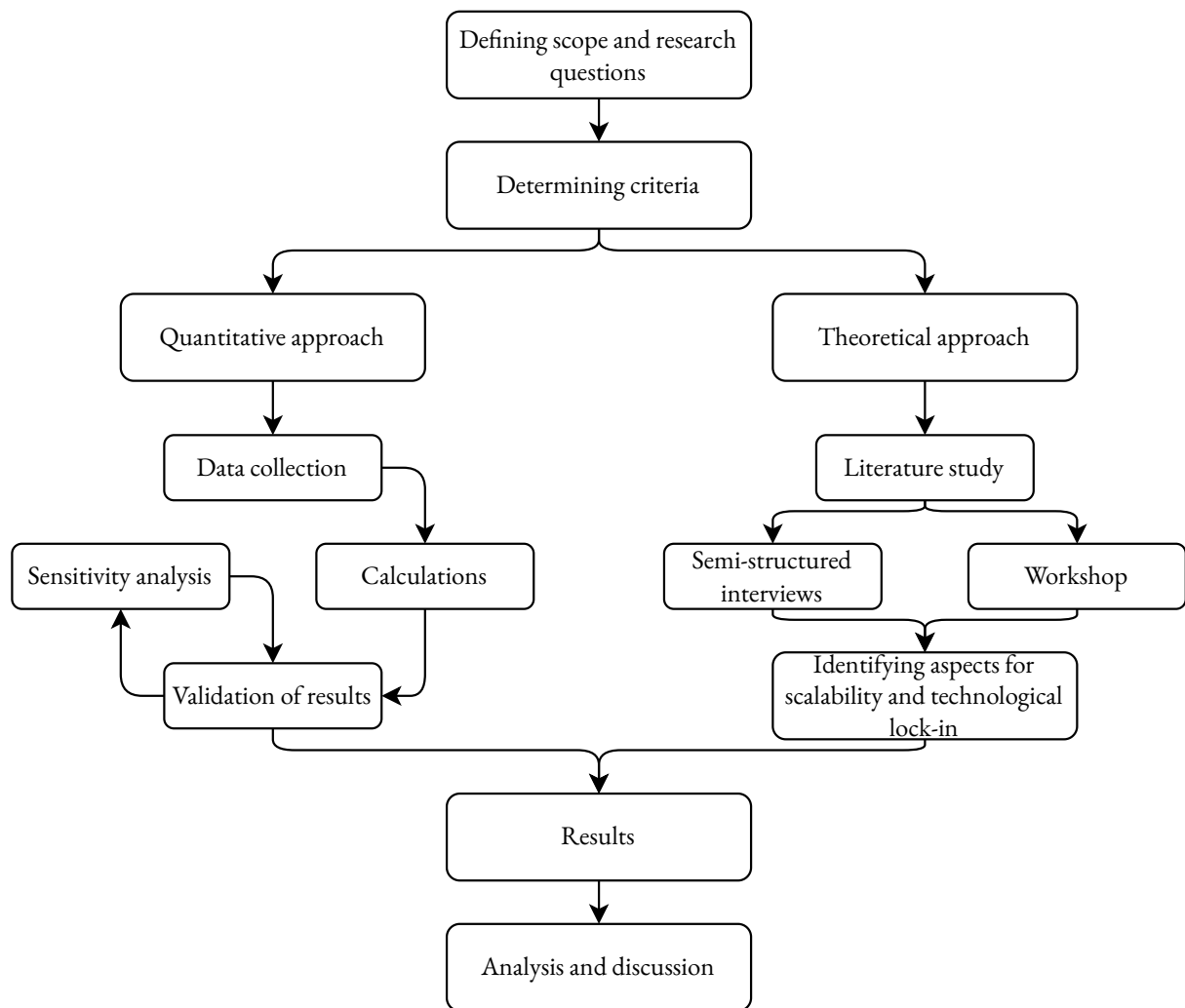


Figure 3.1: Structure of the methodology approach.

The initial stage of the study involved defining the scope and research questions. As the defined purpose was to investigate the different charging technologies, an explorative approach was chosen for this study. According to Patel et al. (ibid.), an explorative approach includes methodologies where the aim is to investigate a subject where there is limited or no prior research on the area in the initial stage. This applied to the study, therefore an explorative investigation was chosen to gain a deeper understanding of the context. This approach allowed the study to be flexible and for revisions to be done during the execution. An explorative study implies attempting to investigate a certain area, with the aim to gain

knowledge that can serve as the foundation for further research (Patel et al. 2019). The flexible approach allowed the scope and research questions to be revised in a later stage. The determination of scope and research questions was done based on an initial literature study and was determined in a consensual manner by the case company and the university supervisor.

The following step was to determine the criteria, with the purpose to obtain a fair evaluation of the charging technologies. Björklund et al. (2012) argues that most studies have limited resources, for instance in terms of time or money, whereas it is essential to choose methods that contribute to achieving the objective the most. The situation of this thesis was conducted in a limited time frame, therefore the chosen methods for investigating the charging technologies, in relation to predetermined criteria. The number of criteria was six, however, if the time was unlimited more areas could be interesting to cover. The themes for the criteria aimed to cover a diverse area, including both a quantitative and qualitative scope. The reason for this decision was for the criteria to complement each other and provide theoretical and practical contributions to the result. Calculations were done for four out of six criteria, and the remaining two were considered from a theoretical perspective. Hence the breakdown in quantitative and theoretical approaches is presented in Figure 3.1. Where the quantitative approach included data collection, calculations, and validations where the calculations and sensitivity analysis could be iterated. The theoretical approach included continuing the initial literature study, to prepare for the interviews and the workshop, as presented later in section 3.5, and section 3.6. From the literature study, interviews, and workshop, important aspects of the two criteria were identified.

The result from each approach was later compiled into a multi-criteria analysis, to be analyzed and discussed. Additionally, the results for each criterion were analyzed and discussed independently and in relation to the other charging technologies. The final step of the study involved integrating and analyzing the results and the adopted methodology, terminating in a conclusion.

3.2 Case study and assumptions

The analysis for the quantitative criteria was based on a case study. The modeling and sizing were adjusted to suit the circumstances of the case surroundings. The reason for this was to attain a realistic case to make the study applicable to a real-world context, and for the result to be accurate. Accordingly, equal conditions contribute to an equitable comparison between the studied charging technologies.

The case study corresponds to a public charging station, located in Sweden close to Stockholm in connection to European route E4. Due to the chosen location of the station, the modeling was considering prices for electricity bidding area SE3. Where the traffic distribution was obtained from E4an. The capacity was 600 kW and the analysis was adjusted to correspond to the installed capacity for each of the charging technologies. Utilization rate refers to the amount of time that the charging station is occupied with charging vehicles. F. Zhu et al. (2023) emphasizes that the station utilization rate is affecting the economic outcome of a charging station. Therefore, this study explored different utilization rates to investigate how they can affect the economic outcome. The estimation used in the study comprised two cases 30% and 60% respectively. The reason why more than one utilization rate was chosen to be included was to further diversify the results, as a prediction of the actual utilization rate of the station is difficult to determine.

A BESS was chosen for the charging technology that involved an external battery. Why energy storage systems (ESS) are important for the future of charging infrastructure is explained in detail in section 2.1.1. The energy storage battery used in this study was assumed to be a vanadium redox flow battery. The assumption was based upon the VRFBs proven abilities to be suited for energy storage, in terms of low storage loss and high efficiencies (International Renewable Energy Agency 2017; Gouveia et al. 2020).

The fleets that were investigated in the analysis are the autonomous fleet, internal CET fleet, and external customer fleet. In the model, internal CET and external customers are determined to refer to the same type of vehicle. As a consequence, the charging time and energy cost for the two fleets were considered to be the same. For the AET fleet, autonomous equipment for each solution was added to the investment cost. To establish a realistic case for the autonomous charging solution, a robotic arm was chosen to be the autonomous equipment used for DC-fast charging and DC-fast charging with external battery. The battery swapping station that was considered in this study was assumed to operate fully autonomously,

therefore no extra equipment was added for the autonomous solution. Which makes it adaptable to the autonomous fleet without further changes in the station.

3.3 Criteria identification and assessment

For comparing the different charging technologies, six criteria were decided. Determination of the criteria was done through discussions with the case company and based on the literature. The purpose of the criteria was to be important for the development of charging infrastructure in Sweden. All of the chosen criteria were applied to all of the charging technologies. However, as mentioned before, four of the criteria were quantifiable, and two were un-quantifiable. Therefore, a multi-criteria analysis was conducted on the quantifiable criteria while the un-quantifiable criteria were researched through a theoretical perspective to build knowledge about strengths and weaknesses regarding the criteria for the different technologies and fleets. The theoretical perspective was based on a literature study, interviews, and a workshop, as presented in Figure 3.1. The aspects affecting the un-quantifiable criteria are presented in the result and later discussed together with the result from the quantifiable criteria, as a final result.

3.4 Literature study

To systematically investigate relevant research a literature study was conducted. Denscombe (2017) emphasizes that a literature study is conducted with the aim of achieving an understanding of existing research and getting an overview of the studied area, an approach which this study follows. According to Patel et al. (2019) a quantitative study is often considered a deductive approach, in which the methodology involves thoroughly reading to formulate questions and hypotheses. Where the methodology for this study included an initial literature review to attain knowledge in the area and with the aim to define the purpose of the study. Furthermore, the identified literature was used for the theoretical background of the thesis and for identifying the important criteria for the analysis. The aim was to discover literature with a variety of perspectives to provide depth to the study.

There are a large number of scientific articles about charging infrastructure for EVs. Sometimes it can be hard to locate literature for a specific subject matter, therefore it is favorable to have a flexible approach (Oliver 2012). Hence, the study included literature from a wide perspective which could, from different standpoints, contribute to the study. The used articles were focusing on HDEVs, but are not limited to. However, a majority of existing research is investigating the influence and development of passenger electric vehicles and their charging infrastructure. For example, some articles cover the electrification of the transportation sector as a strategy toward lowering global emissions which can be used as theoretical background to the problem description. As electrical vehicles are a relatively new research area and the aim was for the thesis to process up-to-date information, the literature regarding charging infrastructure and electric freight was aimed to be from recent years with some exceptions. Figure 3.2 shows the representation of the years of publication for the used literature.

Count of Publication year

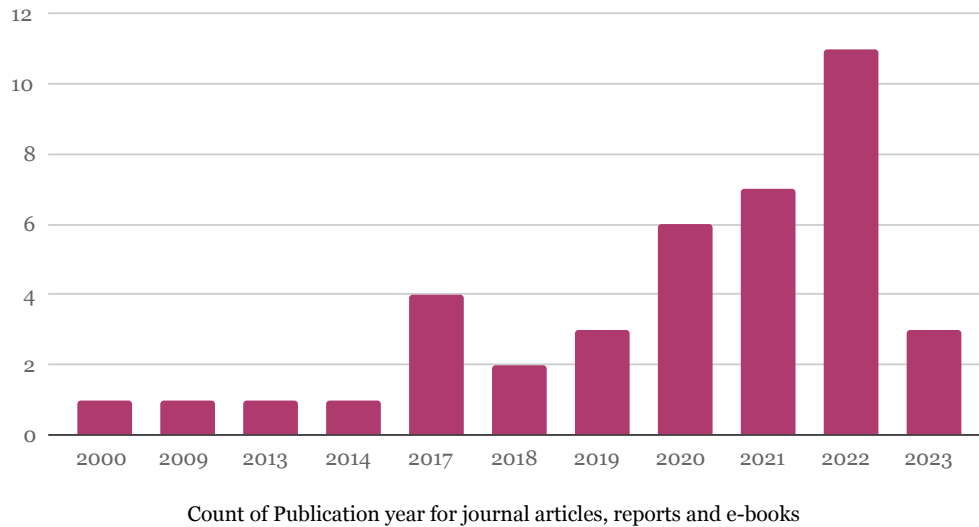


Figure 3.2: Year of publication for the used references, referring to journal articles, reports, and e-books.

The literature presented in Figure 3.2 above, refers to the journal articles, reports, and e-books used for the theoretical contribution in this study. As the aim was to gather recent data, the largest contribution is from the years 2020, 2021, and 2022.

The search process for the literature study was done through the online library at Linköpings University. The site provides accessible e-books and databases, which scientific references can be retrieved from. As Patel et al. (2019) proposes, in general, books provide theories and developed models whereas scientific articles and reports can provide a more up-to-date perspective in the research area. Therefore, this study aimed to focus on scientific research to attain a current situation of the research conducted about HDEVs and their infrastructure. Moreover, books were used as a complement mainly to the methodology aspects of the study. Databases such as Scopus, ScienceDirect, and Web of Science were used for finding scientific research, which is presented in Table 3.1. The reason for this was to ensure that the articles are peer-reviewed and that the authors were familiar with the databases prior to the thesis. Moreover, the study draws upon both e-books, which were accessed through the online library, and physical books that were obtained from the Campus Valla Library. To systematically store the references a reference database was made in Mendeley Reference Manager, where the two authors could manage and share references. Figure 3.3 presents the breakdown between document types for the used references in this study.

Table 3.1 presents an overview of the specifications used for the literature study. In other words, the databases used for finding articles, and the keywords used for narrowing the search process to relevant topics.

Table 3.1: Specifications for the literature study.

Specifications	
Keywords	Charging infrastructure, HDEVs, Freight industry, Electrification, DC-charging, Autonomous vehicles, Battery swapping, BESS, Conductive charging, Energy system, Grid capacity, Limitations
Databases	Scopus, ScienceDirect, Web of Science

Count of document type

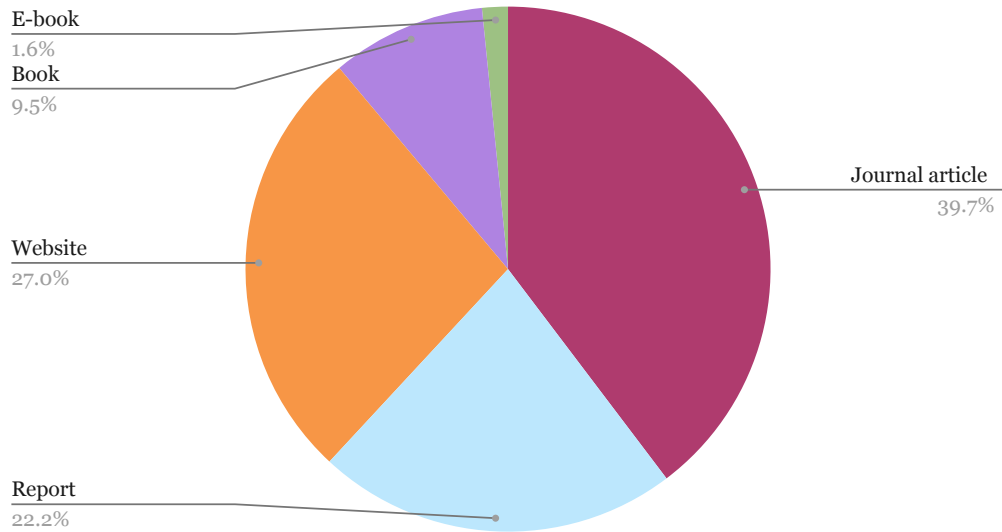


Figure 3.3: The document types used in the literature study.

3.5 Semi-structured interviews

To contribute to more in-depth analysis and to obtain primary data, interviews were conducted. According to Björklund et al. (2012), interviews can make accessible information of primary data, where the information is collected with the purpose to be used in the study. A comprehensive summary of the interviews is presented in the results. The purpose was to complement the literature study. Prior to selecting the interviewees, directives were developed to obtain interviewees within an appropriate area of research. This involved the interviewee having significant insight into the transition toward an electrified transportation sector, primarily concerning HDEVs. Table 3.2 presents details regarding the interviewees, the theme for the interviews, and when the interviews were conducted.

Table 3.2: Details related to the conducted interviews.

Interviewee	Date of interview	Interview topic	Reference
Assistant professor within the field of sustainable logistics, with a focus on the electrification of freight transportation.	2023-03-09	The operation of the logistics in the context of electrification.	Interviewee 1
Professor within sustainability and innovation, and battery swapping as a scientific field.	2023-03-09	The institutional challenges that impede the progress of the electrification of the transportation sector and the necessary measures for accelerating the development.	Interviewee 2

Patel et al. (2019) discusses the importance of the relationship between the respondent and the interviewer. Where this can affect the motive for participating and interest in the interview. Prior to the interview, the interviewees were informed with a brief description of the master thesis, and the purpose of the interview was explained. Furthermore, information on why the interviewees are contacted and how their participation would contribute to the thesis was addressed.

Standardization and structuring are two aspects to take into consideration when preparing for the interview (ibid.). Questions and agenda for the interviews were determined before the interviews. The interviews were semi-structured, which gives the respondents the opportunity to answer and evolve fur-

ther than the specified questions decided prior to the interview. Björklund et al. (2012) describes a semi-structured method where the subject of the interview is decided prior to the situation, but the questions can vary dependent on the outcome of the discussion. This approach is executed in the conducted interviews, where a number of questions were decided but the order and revision of the questions were done during the occasion of the interview. In Appendix A.1, the questions for the interviews are presented. The prepared interview questions were primarily focused on the criteria of scalability and technological lock-in, as the main goal of the interviews was to strengthen the theoretical scope of the study. The conducted interviews were held in Swedish but the interview question presented in Appendix A.1 are translated into English.

Patel et al. (2019) argues that an interview enables the opportunity for the interviewer to help the respondent understand the questions in a way that a questionnaire cannot. This was one of the reasons why interviews were chosen as a method. During the interviews, clarifications were made in order for the discussion to attain valuable dialogues. Furthermore, the questions were adopted in the order that was most suitable for the occurring discussion. The semi-structured approach of the interviews enabled the discussions to be adapted to the knowledge and research area of each interviewee. This approach was chosen as it enabled the interviewees to contribute their specialized knowledge and expertise to the study, thereby enhancing the theoretical contribution.

During the interviews, the function of transcription in Teams was utilized. The function provides a real-time transcript of the interview, at the end of the session it was possible to download a file containing the transcript. To provide an accessible version of the interviews, the transcript file was edited into text. When editing interview material, it is not allowed to add or change any of the content (Jacobsen 1993). However, it is allowed to remove parts or change the sequence of the content (ibid.). An edited and summarized text of the interviews is later presented in section 5, as interview results. To have a fairly revised version of the interviews, the edited texts were sent for the respondents to review and share any disagreements. This was done to attain certainty of the content and retain the interviewees' acceptance.

3.6 Workshop

The aim of the workshop was to contribute to the discussion concerning the results from the literature study, and for the study to be further tailored to the preconditions of the case company. Moreover, the purpose of the workshop was to collect more empirical data for the analysis and discussion part of the study. Therefore the workshop was held at the end phase of the thesis period when all preliminary results were already obtained. The participants of the workshop were exclusively people working at the case company, and the workshop was held in English. The participating persons were considered to have valuable knowledge of the theme of the workshop and therefore contributed to interesting discussions. The participants were specialists in areas such as batteries, CET, charging, and software. As the participating actors possess sufficient knowledge about charging infrastructure and electrified transportation, the presentation could be limited to only cover information specific to the thesis and its results.

The following process steps 1 - 5, provides an explanation of each step conducted to create beneficial conditions for the workshop occasion.

1. Determine the objectives: The objectives of the workshop were to introduce the work to the participants and to attain external reflections and feedback on the work. Furthermore, the objective includes discussing the findings to provide an analyzed perspective and for the thesis to be further adapted to the case company's conditions.
2. Prepare workshop format and material: Conduct a presentation of the thesis and the findings, and determined discussion questions to provide a structured workshop.
3. Invite participants: Provide clear information on the date, time, and agenda. Including pre-read material as a presentation with the determined discussion questions and a draft of the thesis.
4. Conducting the workshop: Conducting an interactive and engaging workshop.
5. Summarize and analyze: Review the collected material from the workshop, as written notes, and recorded material. Conduct a general summary of the workshop and analyze the feedback provided.

The workshop consisted of a 75-minute meeting. As the meeting place was both digital and personal, special planning was needed to enable discussions between the two. Prior to the workshop, discussion questions were determined to conduct a structured workshop. In B.1, the discussion questions can be found. The questions were formulated to direct the discussions toward relevant topics. As the workshop was conducted in a later period of the study, the workshop began with an introduction to the study and the findings. 20 minutes were dedicated to the introduction part. Furthermore, 15 minutes were dedicated to each discussion block. Each discussion block started with a brief introduction, which the purpose was to give perspective to the attendees and for them to provide insightful discussion. The workshop enabled discussions of different perspectives based on the presented material.

3.7 Multi-criteria analysis

Multi-criteria analysis, or Multi-criteria decision analysis (MCA), is a method used for complex decision making (Communities et al. 2009). MCA is based on a complex decision problem for which the analysis is to take into account all related decision factors. The strategic approach for the high complexity of the decision problem and factors makes MCA an appealing method for decision-makers (Doumpos et al. 2014). This is why multi-criteria analysis is chosen for the study. The implementation of a multi-criteria analysis is defined by different phases, which are presented in Table 3.3.

Table 3.3: Overview of the phases for conducting an MCA (Communities et al. 2009).

Phase	Act
1. Define the decision context	Structure the decision problem and identify for what purpose the analysis is conducted to provide a shared understanding.
2. Identify options	The options for the analysis are defined.
3. Identify objectives	The objectives are defined that will result in different criteria that the options are analyzed.
4. Identify criteria	From the objectives, criteria are formulated that further will be investigated in the assessment.
5. Weighting	The importance of each criterion for the decision will be taken into concern by weighting.
6. Calculations	Calculations are made and presented for each criterion. The results from the criterion for each option are compared relatively. Further, the results are ranked between 0 - 1. Where 1 is the strongest
7. Analysis	Analysis of the results and conclusions based on the outcome of the MCA.
8. Sensitivity analysis	Opportunity for sensitivity analysis where parameters are changed.

The implementation of the MCA includes a performance matrix, in which each row represents a criterion and the columns represent the performance of the options in relation to the different criteria. The matrix in general provides information about how well the options perform with respect to the criteria (Communities et al. 2009). The conduction of the MCA in this study was modified, as not all of the phases presented in Table 3.3 were adopted. The performances are represented by numerical scores. The study will define the decision context, and identify the options, objectives, and criteria. Where the options refer to the different charging technologies, and the objectives refer to the area of research that is interesting to investigate. The options for the analysis are DC-fast charging, DC-fast charging with external battery, and battery swapping. The three technologies were chosen due to them being relevant technologies for HDEV charging at a public charging station. It was also of interest to visualize and compare the performance of the technologies in relation to the identified criteria. The objectives were further defined by the six criteria. A delimitation to the study is to exclude the phase involving

weighting, as the criteria will be independently assessed and the weighting is difficult to support and justify. Therefore, the calculations are done and followed by the analysis of the result.

Together with the result from the MCA, literature will be used to further deepen the result and to discuss it from the three chosen perspectives; economical, technical, and environmental.

3.8 Data collection

For data collection, an experimental approach was chosen. In terms of an experimental approach, the found data can be systematically interfered with to be adjusted for the chosen method of the thesis (Scribbr 2023). The implementation of the MCA required specific numbers in order for calculations to be carried out. The process by which the numbers were retrieved refers to the data collection. The process of collecting data was divided into two steps, where the first one focused on information about the charging technologies to define the scope and research questions. The second one included information related to the Swedish energy landscape and the freight industry. A later part of the data collection included the process of where existing literature was scanned to find relevant numbers for conducting calculations for the criteria. This implies numbers corresponding to investment cost, charging downtime, technology lifetime, and climate impact. To increase the validity of the results, suppliers of charging equipment have been contacted to compare the retail price with costs found in the literature. For investment, the contacted company was Kempower which was chosen to be the supplier for the DC-fast charging equipment. Kempower is a company that provides solutions for flexible charging systems and operates on the Swedish market (Kempower 2023b). Which made it a suitable actor for this study.

The following part of the data collection included data for electricity trade and transmission cost, which was needed for the criteria yearly electricity cost. Fees for electricity subscription, performance, and transmission were needed for the calculations and the data was retrieved from Vattenfall. The purpose of this was to replicate the Swedish context in terms of fees. Another part of the yearly electricity cost included electricity spot prices. The spot prices used, are accessed from a Nordpool database, where the authors acquired limited student access. The chosen years for the electricity prices are 2019, 2020, 2021, and 2022, for the bidding area SE3 in the Swedish market.

To be able to distribute the energy use over the day traffic flow information from Trafikverket was obtained. The number of heavy vehicles passing a certain point during an hour was received Trafikverket 2019. A point on road E4 north of Stockholm was chosen as the data point. From the number of passing vehicles a distribution as a percentage of vehicles passing each hour was assumed. The charging demand was assumed to be similar to the traffic distribution of heavy vehicles.

3.9 Return on investment and pay-back time

The return on investment (ROI) and pay-back time were concepts used in the calculations to compare different solutions to each other in the analysis.

The ROI refers to the percentage of the investment that is paid off every year. ROI is calculated as equation 3.1.

$$ROI [\%] = \frac{Net\ savings}{Investment\ cost} \quad (3.1)$$

The pay-back time refers to the number of years needed to make net savings from the investment and is calculated as equation 3.2

$$Pay - back\ time [years] = \frac{Investment\ cost}{Yearly\ net\ savings} \quad (3.2)$$

A higher ROI and a smaller pay-back time are beneficial for the profits of an investment.

4 Criteria for assessing charging technologies

This chapter will present the criteria for the study, the reason behind the establishment of each criterion, and an explanation of what is included in the criteria. Moreover, calculations are conducted to determine sub-results, which will, later on, be implemented in the MCA in section 5.

4.1 Determination of criteria

Figure 4.1 presents an overview of the six criteria together with their decompositions. Two out of six criteria consist of two different factors that are chosen to be important to investigate in relation to the criterion.

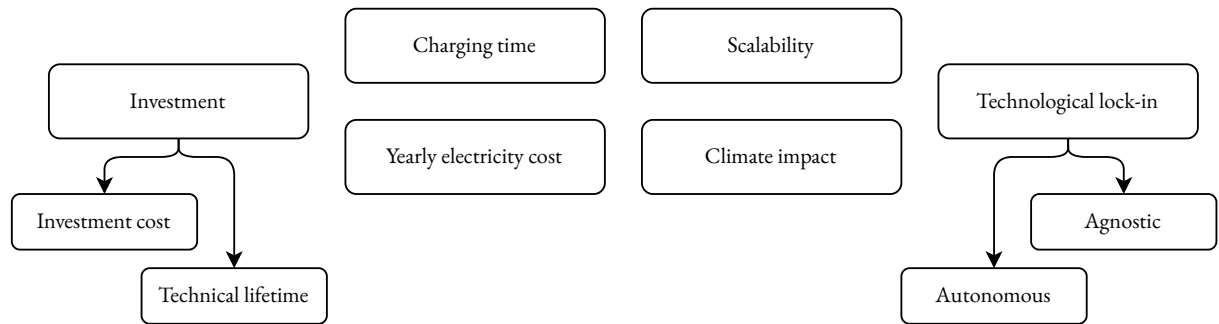


Figure 4.1: Overview of chosen criteria.

Calculations and result for each quantifiable criterion are presented with associated calculations. More specifically this chapter will present numbers on investment, charging time, electricity costs, and climate impact. The quantifications are necessary for the method and will later be used in the MCA. Furthermore, the un-quantifiable criteria will be presented from a theoretical perspective. Which implies the criteria of scalability and technological lock-in. The result from the theoretical criteria will be summarized in important aspects presented later in section 5, and will contribute to diversifying the result by including aspects that are important but cannot be quantified.

4.2 Investment

This part of the study aims to include an economic perspective, therefore the chosen economic factor is the investment cost for the different charging technologies. The investment cost refers to the monetary amount required to implement the solution. Thus, the cost can be an extensive factor regarding the process of deciding upon a future strategy for the charging infrastructure. Additionally, the technical lifetime is chosen to be a factor to include in the criterion of investment. Both investment cost and technical lifetime will complement the system perspective of the investment. As for the structure of the analysis, the two factors of the investment criterion will be considered separately where investment cost will be included in the MCA, and the technical lifetime will be considered in the analysis and discussion.

An electrical vehicle fleet is said to be a cost-efficient alternative for future transportation, despite involving significant investment regarding charging infrastructure (Lutsey et al. 2017). Hence, the economic standpoint is an additional barrier to the deployment of charging infrastructure. The investment and operation of a charging station can be challenging. Especially considering the sparse electricity fleet that contributes to a low utility rate at the charging station (Fossilfritt Sverige 2020). The investment cost and technical lifetime are varying for the different charging technologies.

Table 4.1 shows what cost posts are required to implement each charging technology, except for grid-related costs, which will be addressed in chapter 4.4.

Table 4.1: Cost posts for each charging system.

DC-fast Charging	DC-fast Charging with External battery	Battery Swapping
Power Unit Satellites	Power Unit Satellites	Power Unit Vehicle Battery
Substation [600kW] Grid connection Groundwork Foundation	Energy storage battery Substation [360kW] Grid connection Groundwork Foundation	Substation [360kW] Grid connection Groundwork Foundation Station house
Refuge Cables Electrical installation	Refuge Cables Electrical installation	Refuge Cables Electrical installation

Table 4.1 presents the similarities and differences regarding the components of the three charging technologies. The power unit operates together with the satellites for DC-fast charging and DC-fast charging with an external battery but is independent of battery swapping. The substation connects the charging infrastructure to the grid, which is required for all three charging systems. Cables are needed for each charging system, where different versions contribute to varied cost posts for the systems. Although the cables contribute to varied amounts of investment for each charging system, this will not be addressed in the investment cost. Costs for groundwork, foundation, refuge, and electrical installation are not considered in the summaries of the investment cost. The reason for this is that these are assumed to be equal for each charging technology and thereby will not affect the cost for comparison.

Investment cost as a criterion will be quantified in units of SEK. The investment will be referred to as the cost of components that are necessary for the investigated charging technologies. Table 4.2 presents the cost for components of the charging system.

Table 4.2: Prices of charging system components (Kempower 2023a; Harju Elekter 2023; Vattenfall 2023a; International Renewable Energy Agency 2017)

Investment	Cost
Power Unit and four satellites [SEK]	1 775 040
Robotic arm [SEK]	500 000
External battery [SEK/kWh]	2 405
Battery swapping equipment [SEK]	4 554 911
Substation (500 kVA) [SEK]	1 300 000
Substation (800 kVA) [SEK]	1 400 000
Substation (1600 kVA) [SEK]	1 500 000
Grid connection [SEK/kWh]	380

The data presented in Table 4.2 is gathered from literature and from suppliers of the components. Costs for the power unit and satellite charging system are determined by the prices from Kempower (2023b). For the option of DC-fast charging the case includes a charging system of one power unit and four satellites. A power unit can be connected to a maximum of 8 satellites and can provide a maximum power of 600kW (Kempower 2022a). The satellite charging system used in this case consists of four satellites with two CCS2 outlets each. The investment cost for a robotic arm is assumed to be 500 000 SEK as presented in Table 4.2. This is an estimate based on a price estimate for industrial robotic arms ranging from \$25,000 to \$ 400,000 (EVS 2023; Hitbotrobot 2023), where the price estimate corresponds to simpler specimens and more advanced specimens respectively. The robotic arm used in this study is considered to approximate an investment cost of 500 000 SEK which will correspond to a simpler variant of a robotic arm.

The cost of the external battery is expressed in [SEK/kWh] and corresponds to a price example for the

VRFB. The decision of VRFB as an external battery is motivated and further explained earlier, in section 3.2. International Renewable Energy Agency (2017) has predicted a cost reduction potential for different batteries, and for VRFB the reduction to the year 2030 is expected to decrease by 66% compared with the cost for 2016. As the investment cost of an external battery is currently expensive, it can be expected to decrease as the technology develops. The cost used in this study is the mean of the two costs (for 2016 and 2030) resulting in 2 405 SEK/kWh, as presented in Table 4.2. The assumption is supported by the fact that this study is conducted in the year (2023) which falls between 2016 and 2030. The cost for battery swapping includes all equipment and components needed for deploying a battery swapping station (BSS). The BSSs are capital-intensive (Pham et al. 2022), due to the need for both another structural station house and the required amount of batteries. The substations are dependent on the installed capacity of the charging systems, and therefore three different sizes are presented in Table 4.2. Where the specific capacities needed for each system will be addressed later on.

The summarized investment costs for each charging technology are presented in Table 4.3.

Table 4.3: Investment costs for charging technologies.

Charging technology	AET [SEK]	CET [SEK]	External customer [SEK]
DC-fast charging	5 403 040	3 403 040	3 403 040
DC-fast charging with external battery	11 116 127	9 116 127	9 116 127
Battery Swapping	5 991 711	5 991 711	5 991 111

The investment costs are calculated, and based upon which of the cost posts from Table 4.2 are necessary for implementing each charging technology. Firstly, the total investment cost for DC-fast charging includes one power unit, four satellites, a substation of 800 kVA, and a grid connection of 600 kW. The summarized cost is equivalent to the CET and external customer fleet. Autonomous equipment in terms of four robotic arms is added to represent the total investment cost of DC-fast charging for AETs. Secondly, the investment for DC-fast charging with an external battery is similar to the previous one. The differences are regarding the addition of an external battery, and changes in size for the substation, and the grid connection. The substation needed is 500 kVA and the grid connection needed is for 360 kW installed capacity, the reason for this is explained further in section 4.4.4. The autonomous equipment is added as in the previous case. Lastly, the investment for a battery swapping station includes the cost of battery swapping equipment together with a substation of 500 kVA and a grid connection for 360 kW. The battery swapping station is already considered to operate autonomously which results in equal investment cost for each vehicle fleet. Yang (2022) presents information about that a battery swapping station ranges between \$230 000 to \$630 000 in China. This is similar to the investment cost presented in Table 4.2, with the exception that the investment cost also includes the cost of a substation and a grid connection.

The investigated charging technologies will involve individual technical lifetime regarding the components, accordingly, each technology will be uniquely affected. With the exception of the battery swapping station, where the station as a whole will be considered. This delimitation is foremost based on the limited accessibility of data for battery swapping stations. Presented in Table 4.4 is the expected lifetime of each component in terms of years.

Table 4.4: Expected lifetime for charging system components (Kempower 2023a; Wyatt et al. 2017; Gouveia et al. 2020).

Charging component	Lifetime [years]
Power Unit	15
Satellite	15
Robotic arm	8
External battery	20
Battery swapping equipment	20

Shown in Table 4.4 is that all components needed for DC-fast charging, referring to the power unit and satellites, result in a technical lifetime of 15 years. This lifetime is according to the preventive

maintenance plan of the supplier of the components (Kempower 2023a). In this study, the expected technical lifetime for the external battery is assumed to be 20 years. The assumption is based upon the expected operational lifespan for VRFB which is considered to be 20 years (Gouveia et al. 2020). For the autonomous equipment of the two DC-charging technologies the expected lifetime is assumed to be 8 years, this is based on the operational lifetime for industrial robots (Wyatt et al. 2017). The technical lifetime for a battery swapping station is considered to be 20 years. The technical lifetime in study refers to the actual lifetime of the technology, where the function of the technology is effective and efficient. Therefore, the presented lifetime in Table 4.4 accounts for how long the technology can be used rather than the accounting lifetime. Accounting lifetime, on the other hand, is based on the financial considerations of the technology, which this study does not include.

4.3 Charging time

Charging time is considered a criterion in this study due to the significant differences in charging HDEVs, compared to fueling a conventional truck. The charging time is playing an important role in the transportation system, and is important to consider when deploying charging infrastructure. The charging time will be classified as charging downtime for this thesis and refers to the time required to charge a vehicle. Charging time can be quantified and will be presented in minutes.

The charging downtime in this study refers to the downtime for a vehicle to recharge/swap a battery. For the two DC-fast charging solutions, the charging downtime is calculated from the energy amount representing 20% - 80% state of charge (SOC) divided by the charging power. The charging time is the same for DC-fast charging with and without an external battery. The charging downtime is affected mainly by two parameters; the power output of the charger and the capacity of the electric vehicle to receive power from the charger (Nåbo et al. 2023).

The charging downtime for each technology and for the CET and external fleet is summarized in Table 4.5. However, due to confidential information, the charging time for the AET fleet will not be presented in this study. Although, it can be noted that cable charging and battery swapping technologies for the AET fleet differ, battery swapping is significantly faster due to the technology's characteristics where the battery is swapped instead of recharged.

Table 4.5: Charging downtime for charging technologies for the corresponding vehicle fleet.

Charging downtime [minutes]	AET	CET	External fleet
DC-fast Charging	-	112	112
Battery Swapping	5	5	5
DC-fast Charging with External Battery	-	112	112

Transportation scenarios differ in terms of range and route. The transport characteristics determine the demand for charging solutions (J. L. Liu et al. 2022). Some scenarios are more suitable for a lower charging time, whereas others do not require that. For instance, this can translate into that some are more suitable for cable charging and others for battery swapping. For transports where the range exceeds the battery capacity, cable charging is not sufficient if the time schedules are tight, in those cases, battery swapping recharge is more efficient (ibid.).

4.4 Yearly electricity cost

Electricity cost is a significant cost for HDEVs. Additionally, the electricity cost can differ a lot depending on when the energy is used. Therefore applying different charging technologies and charging patterns will affect the yearly electricity costs, making it an important criterion to consider.

The following section presents yearly electricity cost for the case study of a station with 600 kW installed charging capacity and 30% and 60 % utilization rate respectively are presented. In section 5.4 sensitivity analysis will be presented with varying parameters.

The electricity cost is divided into two parts. One is the cost for electricity trade, concerning the spot price on electricity from the day-ahead market, electricity certificate, taxes, etc. (Konsumenternas energimarknadsbyrå 2022). The second part consists of costs for transmission which includes subscription, performance, transmission, etc. (ibid.). In Table 4.6 the costs for electricity certificates and energy tax are found.

Table 4.6: Electricity certificate and energy tax costs.(Energimarknadsbyrån 2022; Vattenfall 2023c)

	Cost
Electricity certificate [SEK/kWh]	0.032
Energy tax [SEK/kWh]	0.392

In Table 4.7 the transmission costs for the case study are shown.

Table 4.7: Electricity subscription for electricity distribution high voltage (Vattenfall 2023b).

Fee Vattenfall Eldistribution 6-20 kV N3	Cost
Fixed charge [SEK/month]	2400
Monthly effect fee [SEK/kW/month]	27
High load fee [SEK/kW/month]	55
Transfer fee peak price [SEK/kWh]	0.189
Transfer fee low price period [SEK/kWh]	0.066

4.4.1 Differentiation between high- and low-cost prices for electricity trade

Costs for electricity trading have been determined through historical spot prices in the Swedish bidding area SE3. A differentiation between prices has been made, where the prices are divided into high-cost prices and low-cost prices. Historical data on electricity spot prices from the day-ahead market has been used to model electricity trading costs. Data for years 2019, 2020, 2021, and 2022 has been used.

The differentiation between electricity prices is made since the hourly spot prices differ a lot depending on time and day as presented in section 2.1. To differentiate the spot prices, an average price for high-cost hours and low-cost hours during the years 2019 - 2022 is determined. The determination is done by identifying the yearly mean price for each year, including all hours in a certain year. Thereafter a mean price for each date including every hour is determined. Additionally, a mean price for each hour, containing all days over the year is made. By this, dates and hours with a higher mean price than the yearly mean price are identified. High-cost periods are considered to be those hours that occur both during high-cost dates and during hours with a mean higher than the yearly mean. In Table 4.8 the yearly mean for each year, statistical characteristics for the hours, and parameters such as the number of days with different cost differentiation and the different prices. The hours that have a higher price than the yearly mean average price are hours 8-21.

Table 4.8: Parameters for electricity trade costs during 2019 - 2022 (Nord Pool 2023).

	2019	2020	2021	2022	Average
Yearly mean [SEK/kWh]	406	221	672	1379	
Standard deviation [SEK/kWh]	107	199	610	1374	
Median [SEK/kWh]	406	174	517	994	
Number of high-cost days	186	156	117	142	150
Number of low-cost days	179	210	248	223	215
Number of total days	365	366	365	365	365.25
High-cost price [SEK/kW]	0.49	0.45	1.48	3.10	1.38
Low-cost price [SEK/kWh]	0.36	0.14	0.49	0.87	0.47

The electricity costs for each charging technology and fleet will depend on the factors affecting the cost. Referring to usage during high-cost or low-cost hours, and thereby the cost for electricity trade. Also, the transmission costs, which represent the demand of installed capacity [kW], the total amount of electricity used for transmission, and a fixed subscription fee, as presented in Table 4.7.

4.4.2 Differentiation between peak and low price period for transmission costs

Since transmission costs in Table 4.7 are dependent on use during high load periods and peak prices, the electricity usage in this study is differentiated according to the definition that Vattenfall provides. High load periods for Vattenfall are defined as: *Peak hours: Monday to Friday from 06:00 to 22:00 during the months of January, February, March, November, and December. The following days, which may occur from Monday to Friday, are not considered weekdays: New Year's Day, Epiphany, Maundy Thursday, Good Friday, Easter Monday, Christmas Eve, Christmas Day, Boxing Day, and New Year's Eve* (Vattenfall 2023b). Given the definition, the high load fee is included for five months. The transfer fee for the peak price and low price periods respectively concerns the electricity amount used during the two periods. According to the definition, 150 days are considered high load days, and 260 days as normal load days, for 2023. To decide the electricity amount used during those periods the traffic distribution, in Figure 4.2 is used to determine how large share of electricity use is happening during the hours 06-22.

4.4.3 DC-fast charging

With the preconditions of the case study, the station has an installed charging capacity of 600 kW, divided into four CCS2 fast charging outlets with a capacity of 150 kW each. The utilization rate is estimated to be 30% and 60%. While charging 150 kW, limitation in the system results in a transmitted power assumed to be 138 kW.

In Table 4.9 cost parameters for electricity costs for DC fast charging at the station are presented. The list below explains the content in Table 4.9 by presenting the cost parameters for DC-fast charging at the station.

- Daily charging time is calculated from 24 hours a day, 30% respectively 60% utilization rate.
- Electricity amount charged during 24 hours [kWh], means the charged energy from 150 kW charging from four outlets and a daily charging time of 7.2 and 14.4 hours.
- Yearly electricity usage is the daily usage multiplied by 365 days.
- Fixed charge is calculated from the monthly fee multiplied by twelve months.
- Monthly effect fee is calculated from the installed capacity (600 kW).
- High load fee is calculated from the installed capacity (600 kW) and multiplied by five months considered as high load as explained in section 4.4.2.
- Transfer fee peak price refers to the electricity amount used during high load periods.
- Transfer fee low price period refers to the electricity amount used during low price periods.
- Summary grid fees is a sum of all grid fees (fixed charge, monthly effect fee, high load fee, transfer fee peak price, transfer fee low price period).
- Yearly electricity trade cost [SEK], using high-cost hours is calculated from the high-cost price in Table 4.8 multiplied by the yearly electricity usage.
- Yearly electricity trade cost [SEK], using low-cost hours is calculated from the low-cost price in Table 4.8 multiplied by the yearly electricity usage.
- Yearly electricity cost [SEK], using high-cost hours is the sum between the electricity trade cost for high-cost hours and the grid fees.
- Yearly electricity cost [SEK], using low-cost hours is the sum between the electricity trade cost for low-cost hours and the grid fees.

Table 4.9: Cost parameters DC-fast charging

Property	UR 30%	UR 60%
Number of chargers [CCS 150 kW]	4	4
Peak usage [kW]	600	600
Utilization rate [%]	30	60
Daily charging time [h]	7.2	14.4
Electricity amount charged during 24h [kWh]	4 320	8 640
Yearly electricity usage [MWh]	1 576	3 154
Fixed charge [SEK/year]	28 800	28 800
Monthly effect fee [SEK/year]	194 400	194 400
High load fee [SEK/year]	165 000	165 000
Transfer fee peak price [SEK/year]	66 666	133 333
Transfer fee low price period [SEK/year]	80 788	161 577
Summary grid fees [SEK/year]	535 655	683 110
Yearly electricity trade cost [SEK/year], using high-cost hours	2 178 045	4 356 091
Yearly electricity trade cost [SEK/year], using low-cost hours	736 332	1 472 664
Yearly electricity cost [SEK/year], using high-cost hours	2 779 111	5 039 201
Yearly electricity cost [SEK/year], using low-cost hours	1 337 398	2 155 774
Electricity certificate & Energy tax [SEK/year]	668 563	1 337 126

The allocation between high-cost and low-cost hours is estimated by the assumption that charging the vehicles occurs during both periods. To estimate the charging load at different hours the traffic distribution is determined by an estimate of the traffic distribution in connection to the charging site. The Swedish Transport Administration, a state administrative authority in Sweden, provides a traffic flow map for this estimate. The map provides an hourly degree of occupancy for traffic, and data from the E4 road in northern Stockholm, is used. The measurement point used is from 2019, which is the latest data available for the point in issue. The average number of heavy vehicles for each hour is calculated based on the traffic flow. By this average, an average distribution [%] for each hour is determined, shown in Figure 4.2.

Traffic distribution, heavy transports, one day

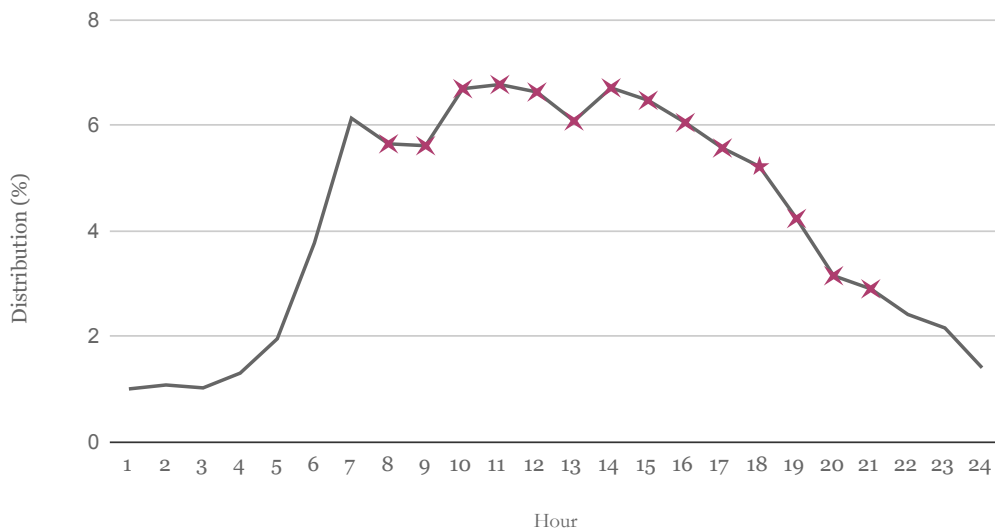


Figure 4.2: Overview traffic distribution and high-cost hours, where high-cost hours are marked with a red cross.

In Figure 4.2 average percentage of traffic distribution from heavy vehicles over each hour is shown, also the high-cost hours are highlighted. The sum of traffic, in terms of heavy-duty vehicles, passing during high-cost hours is 77.8% and 22.2 % during low-cost hours (as defined in section 4.4.1). To include the right contribution from high-cost price and low-cost price, the time for charging is decomposed into three periods, shown in Table 4.10. A visualization of the load profile for the utilization rate of 60% can be seen in Figure 4.3. It shows that the load on the grid is dependent on the hour-to-hour demand, making the majority of the charging takes place during high-cost periods.

Table 4.10: Cost contribution from different time periods.

High-cost dates, high cost hours	High-cost dates, low-cost hours	Low-cost days, any hour
High-cost price	Low-cost price	Low-cost price

Load profile DC - fast charging station

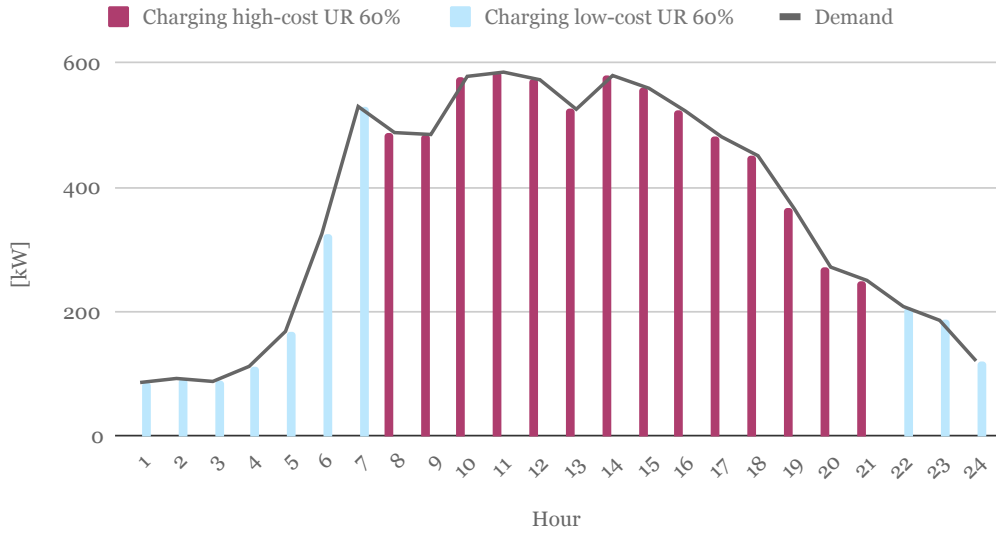


Figure 4.3: Overview of the charging, based on the traffic distribution. Where high-cost charging is marked red and low-cost charging is marked blue.

In the list below abbreviations of parameters involved in the calculations of the yearly electricity costs based on traffic distribution are presented:

- HCP = High-cost price
- LCP = Low-cost price
- HCTS = High-cost traffic share
- LCTS = Low-cost traffic share
- HCD = Number of high-cost days
- LCD = Number of low-cost days
- TD = Number of total days
- ETC = Energy tax and certificate costs

Equation 4.1 shows the calculations made for the contributions of low-cost and high-cost depending on the traffic distribution.

$$Cost_{traf.dist.} = HCP * HCTS * \frac{HCD}{TD} + LCP * LCTS * \frac{HCD}{TD} + LCP * \frac{LCD}{TD} + ETC \quad (4.1)$$

In Equation 4.1 the first term represents the first column in Table 4.10 and considers the high-cost price multiplied by the share of traffic passing during such hours and the share of days considered as high cost. The second term in Equation 4.1 represents the second column in Table 4.10 and considers the low-cost hours during high-cost days, meaning the low-cost price multiplied by the share of traffic passing during low-cost hours and the share of high-cost days. The third term in Equation 4.1 represents the third column in Table 4.10 and considers the costs during low-cost days as the low-cost price multiplied by the share of days that are considered as low-cost.

Equation 4.2 presents the calculation made for cost contribution with utilization rate 30%.

$$Cost = 2713700 * 77.8\% * \frac{150}{365.25} + 1271987 * 22.2\% * \frac{150}{365.25} + 1271987 * \frac{215}{365.25} + 668563 = 2401735 \quad (4.2)$$

Equation 4.3 presents the calculation made for cost contribution with utilization rate 60%.

$$Cost = 5039201 * 77.8\% * \frac{150}{365.25} + 2155774 * 22.2\% * \frac{150}{365.25} + 2155774 * \frac{215}{365.25} + 1337126 = 4415271 \quad (4.3)$$

In Table 4.11 a summary of the results is presented.

Table 4.11: Yearly electricity costs

	Utilization rate 30%	Utilization rate 60%
Yearly electricity costs [SEK]	2 401 735	4 415 271
Cost per MWh [SEK/MWh]	1 523	1 400

4.4.4 DC-fast charging with external battery

The charging solution DC-fast charging with an external battery has the same configuration for charging outlets as DC-fast charging. The station in the use case has an installed charging capacity of 600 kW, divided into four CCS fast chargers with a capacity of 150 kW each. The utilization rate is estimated to be 30% and 60%. While charging 150 kW, limitations in the system result in a transmitted power assumed to be 138 kW. The solution is designed to minimize the installed capacity by dividing the daily electricity usage over 24 hours and using an external battery to even out the usage. In section 5.4.4 a sensitivity analysis of varying battery sizes is made.

In Table 4.12 the parameters that are different between the DC-fast charging station and the DC-fast charging station with an external battery, are shown. Based on the information in Table 4.12 the increased cost for introducing a battery storage solution is 5 713 087 SEK.

Table 4.12: Parameters for external battery setup.

Parameters	DC-fast charging	DC-fast charging with external battery
Installed battery capacity [MWh]	-	2.5
Installed capacity [kW]	600	360
Battery cost [SEK]	-	3 015 494
Cost substation [SEK]	1 400 000	1 300 000
Cost grid connection [SEK]	228 000	136 800

In Table, 4.13 parameters for the yearly electricity cost for the station with an external battery are shown. The list below explains the content in Table 4.13 by presenting the cost parameters for DC-fast charging with external battery at the station.

- Charging time is daily charging time based on a utilization rate of 30% and 60%.
- Electricity amount charged during 24h, means the charged energy from 150 kW charging from four outlets and a daily charging time of 7.2 hours and 14.4 hours respectively.
- Yearly electricity usage is the daily usage multiplied by 365 days.
- Fixed charge is calculated from the monthly fee multiplied by twelve months.
- Monthly effect fee is calculated from the installed capacity (360 kW).
- High load fee is calculated from the installed capacity (360 kW) and multiplies with five months considered as high load as explained in section 4.4.2.
- Transfer fee peak price is related to the electricity amount used during high load periods.
- Transfer fee low price period is related to the electricity amount used during low price periods.
- Summary grid fees is a sum of all grid fees (fixed charge, monthly effect fee, high load fee, transfer fee peak price, transfer fee low price period).
- Yearly electricity trade cost [SEK], using high-cost hours is calculated from the high-cost price in Table 4.8 multiplied by the yearly electricity usage.
- Yearly electricity trade cost [SEK], using low-cost hours is calculated from the low-cost price in Table 4.8 multiplied by the yearly electricity usage.
- Yearly electricity cost [SEK], using high-cost hours is the sum between the electricity trade cost for high-cost hours and the grid fees.
- Yearly electricity cost [SEK], using low-cost hours is the sum between the electricity trade cost for low-cost hours and the grid fees.
- High-cost use [%] is the percentage of electricity used during high-cost hours on any day. Meaning it does not necessarily need to be a high-cost hour by the definition in Table 4.10, where a high-cost hour is happening both on a high-cost day and a high-cost hour. Determined from electricity use during hours 8-21 in Figure 4.4.
- Low-cost use [%] is the percentage of electricity used during low-cost hours on any day. Determined from electricity use during hours 1-7 and 22-24 in Figure 4.4.

Table 4.13: Cost parameter DC-fast charging with external battery.

Property	UR 30%	UR 60%
Number of chargers [CCS 150 kW]	4	4
Charging time [h]	7.2	14.4
Electricity amount charged during 24h [kWh]	4 320	8 640
Yearly electricity usage [MWh]	1 577	3 154
Fixed charge [SEK/year]	28 800	28 800
Monthly effect fee [SEK/year]	116 640	116 640
High load fee [SEK/year]	99 000	99 000
Transfer fee peak price [SEK/year]	60 726	121 451
Transfer fee low price period [SEK/year]	82 863	165 726
Summary grid fees [SEK/year]	388 029	531 617
Yearly electricity trade cost [SEK], using high-cost hours	2 178 045	4 356 091
Yearly electricity trade cost [SEK], using low-cost hours	736 332	1 472 664
Yearly electricity cost [SEK], using high-cost hours	2 566 074	4 887 708
Yearly electricity cost [SEK], using low-cost hours	1 124 361	2 004 281
Electricity certificate & Energy tax [SEK/year]	668 563	1 337 126
High-cost use [%]	58%	58%
Low-cost use [%]	42%	42%

In Figure 4.4 the electricity use profile for the charging station is shown. The grey line visualizes the demand load needed to charge vehicles. The purple line visualizes the peak load, meaning the maximal load installed and able to charge from the grid (360 kW). The blue columns visualize the load grid-to-vehicles. Since the demand exceeds the installed capacity an external battery storage is connected for charging. The red columns visualize charging battery-to-vehicle. The high-cost hours occur during hours 8-21, meaning the external battery also moves electricity use from high-cost hours to low-cost hours by charging during low-cost hours and discharging during high-cost hours. Lastly, the orange columns visualize load grid-to-battery, meaning the charging time for the external battery. The sum of the red columns equals the sum of the orange columns, meaning the charging and discharging of the battery is the same amount. The charging efficiency for transmitting power from the external battery to the charging equipment is assumed to be 100% since VRFB has high efficiency, as mentioned in section 3.2.

Sizing the battery is done by summarizing the purple columns as the size of the needed energy. However, 0%-100% discharge is stressful for the battery, therefore the battery size is dimensioned 20% larger than the required energy.

Load profile 360 kW installed capacity, 2.5 MWh battery size

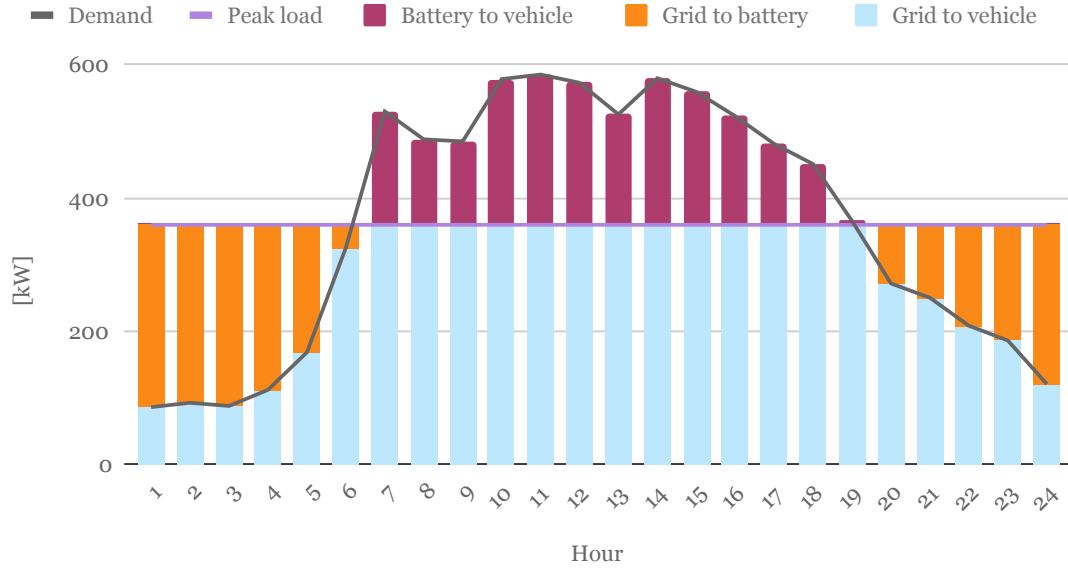


Figure 4.4: Load profile of charging station with external battery, and an installed capacity of 360 kW and utilization rate 60%. The Figure shows the use every hour on the station. Where the grey line shows charging demand, the purple line shows peak load (resulting installed capacity), the orange columns show the load grid to the battery, the red columns show the load from battery to vehicles, and the blue columns show the load from the grid to vehicles.

Deciding what contribution should be represented by the high-cost price and low-cost price depends on two parameters. Partly the cost distribution in Figure 4.10 and partly the High-cost/Low-cost use in Table 4.13. The equation used is the same as Equation 4.1 in section 4.4.3. However, the high-cost share and low-cost share are from Table 4.13 instead of 77.8% and 22.2% as in the previous case, without an external battery.

In the list below, abbreviations of parameters involved in the calculations of the yearly electricity costs based on traffic distribution are presented:

- HCP = High-cost price
- LCP = Low-cost price
- HCTS = High-cost traffic share, meaning the High-cost use in Table 4.13.
- LCTS = Low-cost traffic share, meaning the Low-cost use in Table 4.13.
- HCD = Number of high-cost days
- LCD = Number of low-cost days
- TD = Number of total days
- ETC = Energy tax and certificate costs

Equation 4.4 presents the calculation made for cost contribution with utilization rate 30%.

$$Cost = 2566074 * 58.8\% * \frac{150}{365.25} + 1124361 * 42.2\% * \frac{150}{365.25} + 1124361 * \frac{215}{365.25} + 668563 = 2138879 \quad (4.4)$$

Equation 4.5 presents the calculation made for cost contribution with utilization rate 60%.

$$Cost = 4887708 * 58.8\% * \frac{150}{365.25} + 2004281 * 42.2\% * \frac{150}{365.25} + 2004281 * \frac{215}{365.25} + 1337126 = 4033318 \quad (4.5)$$

Table 4.14: Cost savings yearly electricity cost when introducing external battery storage.

Property	Utilization rate 30%	Utilization rate 60%
Yearly electricity cost DC-fast charging [SEK]	2 401 735	4 415 271
Yearly electricity cost DC-fast charging with external battery [SEK]	2 138 879	4 033 318
Cost per MWh with external battery [SEK/MWh]	1 356	1 279
Yearly savings external battery solution [SEK]	262 856	381 952
ROI [%]	4.6	6.7
Pay-back time [years]	21.7	15.0

As presented in Table 4.12 the cost increase for introducing external battery storage compared to the DC-fast charging case is 5 713 087 SEK. Continuing the yearly savings are 262 856 and 381 952 respectively for the different utilization rates. In Table 4.14 the ROI and pay-back time is presented for investing in an external battery.

4.4.5 Battery Swapping

Since this study is applied to a case study with specific precondition in terms of demand and an application to the Swedish context no certain numbers on installation capacity or electricity use distribution have been found for battery swapping. However, as presented in section 2.3.3 the battery capacity in a battery swapping station can be used to manage peaks and fill valleys in the grid demand. Therefore, this study will assume that the yearly electricity usage is similar to the electricity usage for DC-fast charging with an external battery.

Given the assumptions yearly electricity costs for battery swapping utilization rate 30% are 2 138 879 SEK and with utilization rate 60% 4 033 318 SEK.

4.5 Climate impact from electricity use

In this section, the climate impact of electricity use is determined. Assessing climate impact is an important factor since Sweden has a national approach to reduce the CO₂eq emissions with the electrification of transports as a part of the strategy. However, as presented in section 2.1 the emissions from EVs are only reduced, compared to ICE vehicles, if the electricity originates from fossil-free sources.

Climate impact will be calculated for the utilization rate of 60%, the emissions for the utilization rate of 30% can be assumed to be less. As presented in section 2.1 the heritage of the electricity differs a lot from day to day and hour to hour. Additionally, the more integrated the Nordic electricity system becomes with the European the more dependent the system is on many actors. Resulting in that a larger integration also can involve a more diverse energy heritage, where some countries focus a lot on renewable sources such as wind and solar while others have a larger reliance on fossil fuels for electricity generation. Since marginal approach is appropriate when assessing changes in electricity use, marginal approach is applied in this case. A marginal approach is applied since the external battery solution changes the energy use and moves it from one period of time to another.

Based on the assumption that different energy sources are on the marginal at different periods of time these calculations will use a marginal approach for assessing the emissions, as presented in section 2.1.

The predetermined high-cost hours and low-cost hours, presented in section 4.4.1, will be considered as different time periods where different energy generation sources are on the margin. During low-cost periods wind power is assumed to be on the margin, and during high-cost periods coal condensing power plants are assumed to be on the margin. In Table, 4.15 parameters and results for the calculations can be found.

Table 4.15: Climate impact from electricity use.

Parameter	Value
Emission factor wind power [gCO ₂ eq/kWhelectricity]	12
Emission factor coal [gCO ₂ eq/kWhcoal]	374
Net electrical Efficiency rate coal-fired power plant [%]	36.5 - 41.5
Emission factor coal condensing power plant [gCO ₂ eq/kWh]	959
Emissions DC-fast charging UR 60% [tonne/year]	2360
Emissions DC-fast charging with external battery UR 60% [tonne/year]	1780
Reduction [tonneCO ₂ eq/year]	580
Reduction [%]	25

The content of Table 4.15 is explained in the list below:

- Emission factor wind power [gCO₂eq/kWhelectricity] are the climate emissions emitted from wind power generation, 12 gCO₂eq per kWh electricity (Naturskyddsforeningen 2021).
- Emission factor coal [gCO₂eq/kWhcoal] are the emissions from the combustion of coal.
- Net electrical efficiency rate coal-fired power plant is the efficiency rate for converting coal to electricity (Lecomte et al. 2017).
- Emission factor coal condensing power plant [gCO₂eq/kWh] is based on the emission factor from coal and the efficiency rate in a coal condensing power plant. An average value from the range of net electrical efficiency rate is used. The value refers to the emissions from electricity generated from a coal-condensing power plant.
- Emissions DC-fast charging UR 60% [tonne/year] are the CO₂eq emissions from electricity at the DC-fast charging station with a utilization rate of 60 %.
- Emissions DC-fast charging with external battery UR 60% [tonne/year] are the CO₂eq emissions from electricity at the DC-fast charging station with external battery and the utilization rate of 60 %. The use during high-cost hours is accounted for emissions from coal-condensing power plants on the margin and the use during low-cost hours is accounted for emissions from wind power plants.
- Reduction [tonneCO₂eq/year] are the reduced emissions introducing an external battery.
- Reduction [%] refers to the percentage reduction.

For DC-fast charging the load profile, presented in Figure 4.3 is used to determine how much of the energy is used during high-cost hours (8-21) and how much of the energy that is used during the remaining low-cost hours. The high-cost energy amount is multiplied by the emission factor for the coal condensing power plant in Table 4.15 and the low-cost hour energy amount is multiplied by the emission factor for wind power in Table 4.15.

In Figure 4.5 a comparison of the emissions from the stations is shown.

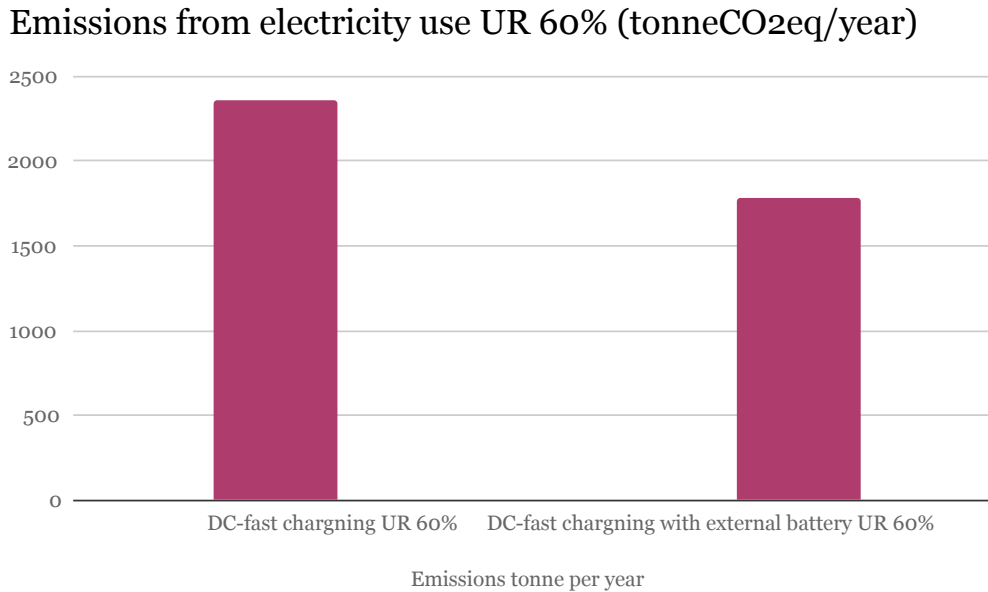


Figure 4.5: Visualisation of the emissions from electricity use at the DC charging stations with a utilization rate of 60%.

4.6 Scalability

The concept of scalability refers to the ability of a system to expand or to increase the number of elements or objects in the system (Bondi 2000). Applied in this study, scalability refers to the possibility of up or down-scaling the charging station to supply a change in the demand. For the DC-fast charging solution and DC-fast charging with external battery, the scaling could involve both a change of the installed capacity or a changed number of outlets for charging the vehicles. Whereas for battery swapping, the scaling involves a modified number of batteries at the station. This criterion is considered difficult to quantify and will thereby be investigated from a theoretical perspective. This section is based on the literature study, where key aspects will be identified as the result. The criterion is chosen to be investigated how adaptable the charging stations are to changing demand and market conditions. Where a non-scalable system can result in increased labor costs or reduced service quality, potentially causing delays or missed revenue opportunities for the actor (ibid.). As for the context of charging technologies and infrastructure, this can involve changes in groundwork, installed grid capacity, or moving the charging station. That implies that scalability is one factor that is necessary to take into consideration when establishing a future strategy for charging technology infrastructure.

As the electrification of the transportation sector is growing, there is a possibility that there is a need to increase the demand for charging possibilities. Where charging stations implemented early and designed for the current demand, could be insufficient for the future. Therefore, it is a prerequisite to include the possibility of up-scaling a charging station when deploying a station in a developing market, in order not to miss revenues from emerging market opportunities. A study conducted by Lidström et al. (2022) presents that a majority of actors are considering the possibility to expand in the initial stages and prepare for such a situation. The study presents measures such as dimensioning the power centrals and cables to be suitable for an increased capacity and preparing pipes in the groundwork (ibid.). Additionally, a charging station that offers cable charging requires the vehicles to be positioned at the station for a longer time. As described in section 4.3, the charging downtime for an HDEV charging at a DC-fast charging station, or a DC-fast charging with external battery station, comprises 112 minutes. This implies that the vehicle will be stationed at the charging station for at least 112 minutes each time. To upscale such a charging station, would include an increased need for geographical space in connection to the site. Lidström et al. (ibid.) emphasizes that geographical space can be noticed as an obstacle when scaling up charging solutions. Especially when referring to charging stations dedicated to HDEVs, where the trucks are in need of a larger spatial area. DC-fast charging will favorably be located along roads where the

charging is needed, as mentioned in section 2.2.1. Consequently, it could emerge difficulties in expanding a charging station.

Battery swapping as a charging technology can be considered easy to scale in such a way as the scaling process involves an increasing number of batteries at the charging site. This approach will in fact not affect the grid capacity as much as the up-scaling of on-demand cable charging, since the batteries in a battery swapping station can be scheduled to a flexible charging pattern. As presented in section 4.3 the swapping time is 5 minutes. Since the downtime for a vehicle is reduced significantly, compared to cable charging, it implies that battery swapping as a charging solution overcomes the difficulties DC-fast charging stands in front of, related geographical space.

Battery swapping in a wider context can be complex, as various manufacturers have their unique setup for the compatibility requirements for the batteries, where it can be challenging to locate batteries that have the same condition and meet the necessary compatibility criteria (A. Ahmad et al. 2018). Hence, the battery composition and size can be seen as an obstacle to up-scaling battery swapping. At the same time, battery swapping on a large scale is dependent on standards. Specifically referring to the battery capacity and size used for the battery swapping procedure. International Energy Agency (2023) argues that this could be noted as a hindrance to competitiveness for the original equipment manufacturing (OEM) companies. Owing to that manufacturers often have specific designs on the sizing and capacity for the batteries. Where international standards would require the manufacturers and operators to act coherently.

The nascent market for charging technologies requires new business models and cooperation between players. Battery swapping can require a new business model in terms of the ownership of the battery, due to the changes in conditions where the vehicle does not have to be present when the charging of the battery is occurring. This means that a battery swapping vehicle does not operate with the same battery, in contrast to cable-charged EVs. However, the business model can be an obstacle to scaling up battery swapping. International Energy Agency (ibid.) discusses that the business model, battery as a service, could be based upon a subscription fee. Where this could result in lowered costs for the vehicle buyer. A report from Nåbo et al. (2023) means that the management of the loading does not have to be done by the depot owner, as this task can be outsourced to a separate operator. A business model for battery swapping could include a subscription to batteries, as described in section 2.3.3. Where customers who own an HDEV suitable for battery replacement are offered a subscription to a battery replacement service. This option allows the customer to buy or rent a battery separately in an already competitive market (ibid.). However, the success of large-scale battery swapping can be hindered by the different ways in which chosen business approaches and models. Which can lead to various barriers and challenges regarding scalability.

In the context of scalability, International Energy Agency (2023) argues that the capacity of up-scaling will be a necessity as the demand for charging facilities for HDEVs increases. DC-fast charging is considered suitable for the current conditions in Sweden, but there are complications for large-scale use in future scenarios when referring to limitations in the grid. Where it could be favorable to take advantage of an external battery to achieve a more flexible energy use, as mentioned in 2.1. Currently, there are extensive difficulties in Stockholm, southwestern Skåne, Mälardalen, Uppsala, and Gothenburg, leading to hinders for company establishments. As mentioned in section 2.1 electrification of heavy transports runs large a risk to be challenged by insufficient capacity, which X. Liu et al. (2021) describes as a crucial enabler for the development. Therefore limitations in grid capacity can be seen as a hindering factor for the up-scale charging infrastructure, especially for DC-fast charging with no energy storage to manage the load. DC-fast charging with an external battery and battery swapping could overcome some of the challenges since they have the capacity for load management in their characteristics.

4.7 Technological lock-in

Technological lock-in as a criterion, in this study, refers to the potential for investments in a particular solution to lead to a situation where it becomes difficult to adapt to market changes or new standardization measures. The decomposition of technological lock-in consists of two factors; agnostic and autonomous. The criterion will be considered from a theoretical perspective through a literature review and the current state of regulations and standards affecting the development of charging infrastructure in Sweden.

Agnostic refers to the ability of a charging infrastructure solution to reach a diversity of different users. The more agnostic a solution is the larger number of vehicles that can use the facility. One example, in the context of this study, is that battery swapping requires vehicles suited for the charging technology, which might reduce agnosticism. Autonomous refers to the ability to conduct the charging solutions autonomously, currently or in the future.

Policies and regulations are necessary for charging infrastructure development but also important factors to consider when assessing the risk of technological lock-in. There may be a risk of investing in a technology and later face restrictions or standards not being in line with the strategy, leading to a technological lock-in. Therefore a mapping of current policies is conducted. Table 4.16 presents some of the current policies that affect the electrification of the transportation sector and public charging infrastructure for HDEV, together with a short description and the policy type. The mapping includes both Swedish policies and policies by the European Commission.

Agenda 2030 aims for the sustainable development of all sectors and to provide a unified action for the involved countries (Regeringskansliet 2021). Motives for a sustainable transportation sector can be found in different parts of the agenda, referring to sustainable cities, the increase of renewable energy in transportation, and the development of infrastructure. Sweden has an ambitious approach and is seen as a pioneer country in a global context. Target 9 addresses a resilient infrastructure, sustainable and promoting industrialization, and innovation (ibid.). The target is further divided into sub-targets which address different parts of the main aim. The Swedish contribution to the target involves efforts such as sustainable transportation and investments in sustainable infrastructure.

The Swedish Environmental Protection Agency provides financial support called Klimatklivet which can be used for various climate-related investments until 2026 (Naturvårdsverket 2023b). For instance, Klimatklivet can support the development of charging infrastructure, to give subsidies for public charging and for private DC-fast charging for HDEV (Energiforsk 2022). The policy is not limited to measures for the electrification of the transport sector, but also hydrogen, biofuels, and actions contributing to a more efficient transport system. (Naturvårdsverket 2023a). As for now, Klimatklivet has supported the deployment of 36 000 charging stations, where 15 500 are public charging stations, for passenger EV (ibid.). The aim for Klimatklivet corresponding electric vehicles is to provide support and ease the deployment of charging infrastructure and as a result lower CO₂ emissions. The support estimates to lower the emissions by 99 000 tons on a yearly basis (ibid.). Noteworthy is that Klimatklivet mainly focuses on passenger EVs but can be utilized for investments in charging infrastructure for HDEVs as well.

The reduction obligation (Swedish: Reduktionsplikten) is an administrative policy that was implemented in 2017 (Sveriges Riksdag 2017). The policy aims to increase the number of renewable fuels and reduce emissions from the transportation sector in Sweden. The process in which this is succeeded involves defined levels of increasing the blend of biofuels and renewables in gasoline, diesel, and kerosene (Energimyndigheten 2023). The reduction obligation provides levels of the minimum allowed emissions for the different fuels, where the suppliers need to ensure that they are not responsible for emissions exceeding their limits each year (Sveriges Riksdag 2017). Fuel suppliers who are unable to meet the reduction obligation demands receive a reduction obligation fee (ibid.). The fee includes a cost per kg of CO₂ equivalents for the emissions that have not been met, but a maximum of 7 SEK per kg of CO₂ equivalents. The purpose of the policy is to apply a lifecycle perspective on the use of fuels, to lower emissions and increase the number of renewables. As the policy includes limits on allowed emissions, this can act as an enabler and accelerator for the transition towards an electrified transportation sector. As blended biofuels are more expensive than fossil fuels, the consequences of the reduction obligation can be increased fuel prices. The result contributes to a resilient market for electricity and a competitiveness of electricity as fuel for vehicles. Therefore the reduction obligation indirectly affects the HDEVs and charging infrastructure.

To support the financial concerns of electric freight the Swedish Government has proposed a policy called Klimatpremien. Klimatpremien will provide financial support for companies, regions, or municipalities, buying heavy-duty vehicles that are either fueled by bio-ethanol, natural gas, or electrical energy (Regeringskansliet 2020). The support can be granted up to 20% of the investment price for the vehicle.

The public support for electrification pilots provided by the Swedish Energy Agency is given for two types of projects, (1) deployment of public infrastructure for either charging stations or hydrogen refueling

Table 4.16: Mapping of existing policies regarding electrification of the transportation sector.

Policy	Type	Motive
Agenda 2030	Informative	Agenda 2030 refer to a global Agenda for sustainable development for people, the planet, prosperity, peace, and partnership (Regeringskansliet 2021). The agenda includes 17 targets assessing different areas of sustainability and was defined in 2015 (Regeringskansliet 2021).
Klimatklivet	Financial	Financial support provided by the Swedish Environmental Protection Agency given for initiatives on technologies that contribute to fossil-free solutions and environmentally friendly solutions (Naturvårdsverket 2023b).
The reduction obligation	Administrative	A regulation which targets a reduction of greenhouse gases from gasoline, diesel, and kerosene (Sveriges Riksdag 2017). The policy intends to increase the number of renewable fuels in the Swedish transportation system.
Klimatpremien	Financial	Financial support for companies, regions, or municipalities buying heavy-duty electric vehicles (Power circle 2022a).
Regional Electrification pilots for HDV	Financial	Financial support for the deployment of charging infrastructure. Provided by Swedish Energy Agency with the aim to accelerate the electrification of freight transportation (Swedish Energy Agency n.d.).
Vita sträckor	Financial	Financial support provided by The Swedish Transport Administration with the goal to ensure secure charging infrastructure on the roads in Sweden (Power circle 2022a).
Connecting Europe Facility (CEF)	Financial	A European Union policy which includes a program that supports the development of infrastructure and funds investments regarding the deployment of infrastructure in Europe (The European Commission 2022). The program supports the development of transport, energy, and telecom, where the energy includes investment support for charging infrastructure (The European Commission 2022).
Alternative Fuels Infrastructure Regulation	Administrative	EU-regulation which includes mandatory targets for the EU member states (European Commission 2023b). The regulation includes targets for both electrified transports and hydrogen-powered transportations (European Commission 2023b). Specific targets for infrastructure for HDEVs are defined and included in AFIR.
Global Drive to Zero	Informative	A program that aims to push the adoption of zero-emission vehicles. The program target a global market of vehicles, and is driven by the Clean Energy Ministerial and CALSTART (Drive to Zero 2023).
Fossilfritt Sverige	Informative	Fossilfritt Sverige, an informative policy, in which an initiative where Swedish industries have joined forces to become fossil-free and climate-neutral (Fossilfritt Sverige 2022). The initiative consists of 22 road maps individually formulated for each industry. Where a specific road map is designed for the automotive industry and heavy-duty electric vehicles.
Green Deal Industrial Plan	Informative	A plan as a part of the European Green Deal with the aim for increasing manufacturing and installation of net-zero products and energy supply.
2030 zero-emissions target	Informative	2030 zero-emissions target for new city buses and 90% emissions reductions for new trucks by 2040. A target by the European Commission is in line with the European Green Deal with the aim to present more stringent emission standards for all new HDVs.

stations or, (2) optimization projects of logistics that enable heavy-duty electric transportation within areas with extensive freight transportation needs (Infrastrukturdepartementet 2023). Therefore, the financial incentive is not given for projects regarding depot or semi-public charging stations. The charging point for the project refers to a point where an electric vehicle can be charged or where the battery in an electric vehicle can be replaced (ibid.). Accordingly, regional electrification pilots for HDEV can support projects involving battery swapping as charging technology. One precondition of the support is for actors to coordinate projects and act together for the electrification pilot (Swedish Energy Agency n.d.). The support is suitable for all actors, with the exception of private persons, and the subsidy corresponds to the total investment cost for the electrification pilot (ibid.).

Connecting Europe Facility (CEF) is a program provided by the European Union and works as a funding instrument (European Commission 2023c). The policy functions to support the development of infrastructure along the interconnected trans-European network (TEN-T) in different areas. The CEF policy provides financial support for CEF energy, CEF transport, and CEF digital services (ibid.). The financial incentives are addressing projects aiming for the development of high-performance, sustainable and efficient networks along the TEN-T (The European Commission 2022). Furthermore, it aims to act as an enabler for the targets regarding decarbonization. Figure 4.6 shows the core network of the trans-European network in Sweden.



Figure 4.6: TEN-T core network Sweden (European Commission 2022).

Figure 4.6 provides an overview of Swedish roads which are included in the trans-European network. Projects connected to these roads can be supported by the CEF program. While the policy includes support for transport, energy, and digital services the allocation of funding primarily has been to transportation (ibid.). €23300 M has been funded to be directed to CEF transportation, where €412.7 M has been assigned to Sweden (ibid.).

AFIR aims to help coordinate the central management of strategic charging infrastructure and interoperability, for all members of the European Commission (International Energy Agency 2022). In March of 2023, a new Regulation for the deployment of alternative fuels infrastructure was agreed upon by

the European Parliament and the Council, which proposes a mandatory deployment target for charging infrastructure of both EVs and hydrogen-powered vehicles (European Commission 2023b). The regulation involves a main target related the electric freight, these can be described as accomplishing a sufficient charging infrastructure network for transportation fleet with full interoperability (European Union 2023). The new regulations aim to provide sufficient charging stations along the Trans-European Transport Network with a minimum capacity of 360 kW for HDEVs by 2030 (European Commission 2023b). Sub-targets are formulated to involve deployed charging stations by varied distances for a sufficient charging network along the TEN-T. Where AFIR will include requirements for charging stations across the TENT-T network (International Energy Agency 2023). Furthermore, AFIR will help ensure that the charging stations are safely deployed and secure parking areas (European Commission 2023b). AFIR is a type of administrative policy that includes mandatory targets for the member states of the EU. The revised proposal of AFIR in March 2023 provides increased support for charging infrastructure, especially for HDEVs. Changes in the regulation involve a gradual deployment of infrastructure covering the TEN-T area, with the aim to provide sufficient infrastructure for HDEV (European Union 2023). This is a contrast to the earlier targets which have been focused on charging infrastructure appropriate for light vehicles rather than heavy-duty. Furthermore, the proposal of the AFIR from 2023 involves changes regarding standards for a unified approach (ibid.).

Fossilfritt Sverige provides a specific road map for the electrification transition of the transportation sector (Fossilfritt Sverige 2022). The organization Mobility Sweden is responsible for the road map and the processes involved in its implementation (ibid.). The road maps summarize opportunities and challenges regarding each industry and present potential solutions. Regarding the necessity for an electrified transportation sector, Fossilfritt Sverige emphasizes the importance of the involvement of the government. Where a national plan for infrastructure is crucial, which should include specific aims and development of depot, semi-public, and public charging points (Fossilfritt Sverige 2020). Furthermore, they emphasize the importance of efficient freight. These strategies aim to meet the formulated climate targets in Sweden regarding the reduction of emissions from the transportation sector by 70% from 2010 to 2030 (ibid.).

The Green Deal Industrial Plan was announced in February 2023 and aims to support Europe's work towards climate neutral (European Commission 2023a). The strategy is built upon four pillars; faster regulatory circumstances, financial support, improved skills, and open trade (ibid.). The plan could affect the development of charging infrastructure in different ways. For instance, a quicker way of admitting permits or financial support for projects. International Energy Agency (2023) describes that the financial part of the plan could be used for allowing subsidies and support for businesses to compensate for increased energy prices or reduce electricity demand.

As mentioned in section 2.4, for a successful implementation of policies, a policy mix is desired. Presented in Table 4.16 the identified policies affecting charging infrastructure are mainly economical, foremost in terms of financial support. All of the presented policies are influencing the development of charging infrastructure in Sweden but in different ways. A study by Borlaug et al. (2022) implies that policymakers play an important role when deciding on policies and subsidies. Mentioned in the article is that it is favorable for electric transportation to be supported by stakeholders and policymakers to invest in research and technologies that stimulate both vehicles and infrastructure (ibid.).

The agnostic perspective for battery swapping can be considered challenging, thus the technology requires specific solutions for both vehicle, battery, and connector. J. L. Liu et al. (2022) emphasizes three main characteristics needed for battery swapping stations; compatibility, intellectualization and high efficiency. Where the authors enhance the importance of unification of the components to provide charging solutions for different vehicles operating at the station (ibid.). This would affect the interoperability of different vehicle fleets operating at the station, such as the autonomous fleet, and the internal and OEM fleet. Battery swapping as a charging technology will require a connector-specific solution, which means that the technical aspects of the station and the vehicle must be coherent with each other (Pham et al. 2022). Accordingly, the battery-swapping solution lacks adaptability when the battery is integrated into the vehicle. Additionally, as mentioned in section 2.3.3, the swappable battery can be placed in different positions in the vehicle which can act as a hindrance to the agnostic aspect. The lack of adaptability contributes to a hinder when expanding the technology in a wider context (Arora et al. 2021a). Where standardizations for battery packs can be considered a precondition for the battery swapping solution to achieve interoperability. In China, the development of standards lagged behind the development of technologies for battery swapping, which has resulted in developments of industry standards (J. L. Liu

et al. 2022). However, policy standards are issued in China but no standardization in the field has been stated (J. L. Liu et al. 2022). In contrast, this could lead to technological lock-in as it needs a unified construction and design.

Despite the obstacles for standardization for the vehicles adopting battery swapping, the circumstances for a vehicle intended for Battery swapping, include the battery integrated into the vehicle can either be swapped or charged by cable (ibid.). This contributes to a choice of charging solution, where the route's characteristics can determine if cable charging or battery swapping is the most efficient for a certain case (ibid.). This condition can be noted as a flexible factor regarding vehicles intended for battery swapping, where there are opportunities to choose among the technologies, rather than choosing one technique.

J. L. Liu et al. (ibid.) emphasize that the development of charging infrastructure can cause an imbalance between countries with different economic landscapes in Europe. Furthermore, electrification of HDEVs is in the initial stage but as development proceeds, new obstacles will be identified. Transportation and travel between countries will be problematic if not charging infrastructure is standardized and evenly distributed. Standardization of components at charging stations and in vehicles is a necessity for wider implementation. Especially when developing charging infrastructure in a wider context and for it to be efficient over national borders.

5 Result and Analysis

This chapter will present the findings of the thesis, it will include the MCA in the form of a table. Lastly, the sensitivity analysis will be presented.

5.1 Multi-criteria analysis of quantifiable criteria for charging technologies

The results from the multi-criteria analysis are presented in Table 5.1. Where the charging technologies are compared against the quantifiable criteria; investment, charging time, yearly electricity cost, and climate impact. The independent results for the three fleets are reflected by one value for each criterion and charging technology.

Table 5.1: Result from MCA.

Criteria/Technology	DC-fast charging	DC-fast charging with external battery	Battery swapping
Investment	1	0.4	0.6
Charging time	0.04	0.04	1
Yearly electricity cost	0.9	1	1
Climate impact	0.8	1	1

The results presented in Table 5.1 summarize how each criterion performs for each charging technology. The numbers presented are converted to absolute numbers based on the result presented in section 4. The scores range from 0 - 1, with 1 representing the best result. The result shows that investment scores 1 for DC-fast charging, which implies the lowest investment cost. DC-fast charging with external battery scores 0.4 and battery swapping 0.6. This implies that DC-fast charging with external battery includes the highest investment cost which is a result of the immense investment referring to the battery energy storage solution. For the criterion charging time, battery swapping scores 1 in comparison to DC-fast charging and DC-fast charging with an external battery which scores 0.04 respectively. The reason for this is due to the radically short charging time accounted for by battery swapping. Yearly electricity cost scores 1 for both DC-fast charging with an external battery and battery swapping. By contrast, DC-fast charging scores 0.9. This result is affected by the fact that the yearly electricity cost is considered the same for DC-fast charging with an external battery and battery swapping, where the technologies enable flexible energy with the possibility to evade high-cost periods. For the criterion climate impact, the solutions DC-fast charging with external battery and battery swapping scored 1 since they have storage and flexibility possibilities while DC-fast charging is more characterized by on-demand charging and thereby score 0.8 in the comparison.

5.2 Implications from scalability and technological-lock in

Table 5.2 presents the summarized aspects affecting both un-quantifiable criteria scalability and technological lock-in.

The results show that the main aspects affecting scalability refer to grid limitations and geographical limitations for the DC-fast charging solutions. Whereas, for battery swapping, the aspect of compatibility is considered. For technological lock-in, standards, policies, and market changes are important aspects regarding every technology. Where standards affect the deployment of charging infrastructure in terms of standards for components, grid integration, and safety measures. Furthermore, policies are important to consider for the opportunity to achieve financial support or consider regulations that affect the deployment. Market changes are similarly important to consider, where the demand or the supply could change. Independently, for battery swapping, considerations about the business model are an identified aspect that could result in a situation of technological lock-in.

Table 5.2: Aspects affecting scalability and technological lock-in.

	DC-fast charging	DC-fast charging with external battery	Battery swapping
Scalability	Grid limitations, geographical limitations, Policies	Geographical limitations, immature technologies	Require compatibility, policies
Technological lock-in	Standards, policies, market changes	Standards, policies, market changes	Standards, policies, market changes, business model

5.3 Interview study

The following section is a compilation of two interviews held with researchers as described in section 3.5. The result from the interviews will be synthesized later in the analysis and discussion.

5.3.1 Interviewee I

The interviewee argues that the primary hinder to the electrification of Swedish heavy transportation is the cost factor. The initial investment cost for electric heavy vehicles is significantly higher. However, extensive research suggests that electrified logistics transports will be profitable in the long term. This is because their operational costs are lower, which will enable them to offset the higher initial cost of HDEV.

Moreover, the interviewee elaborates further on the limitations of HDEV, which pose challenges to operational efficiency, particularly in terms of range and load capacity. The interviewee maintains that these limitations may become problematic as transportation flows become more diversified. For example, if a transportation flow covers 300 km one day and 600 km the next, it is unlikely that the same electric vehicle will be able to handle both distances, as vehicle batteries are typically dimensioned for specific ranges, in contrast to traditional ICE HDV. The interviewee suggests that the challenge lies in finding ways to make these diverse transportation needs work within large systems, where many factors must align.

When asked about the potential inconvenience of downtime for cable charging, the interviewee suggested that battery swapping could be a solution that has seen significant development. However, the interviewee emphasized that in Sweden, the truck manufacturing industry's major OEMs currently hold a lot of influence over the introduction of battery swapping. If these OEMs do focus on other solutions for HDEV in Sweden, rather than Battery Swapping, the technology will likely face significant obstacles in being introduced. Furthermore, the interviewee suggested that the truck manufacturing industry is closely tied to Swedish culture, which may cause resistance and difficulties when implementing new technology shifts in the industry.

The interviewee also contemplated the "logic of logistics," specifically the current system where a driver drives for four and a half hours takes a break, and then continues driving. This system may not be compatible with cable charging and may need to be altered for a future electrified transport system. According to the interviewee, cable charging in combination with on and offloading for regional transports seems to be a viable solution. However, to achieve sustainable transportation in the future, the interviewee emphasizes the need for a combination of technologies such as battery swapping, biogas, and hydrogen alongside cable charging and electrification.

Additionally, the interviewee reflects on the standardization of charging infrastructure. Regarding cable charging standardization, the charging socket and contact are what has to be agreed upon. The interviewee share that this process is ongoing on both the Swedish and EU levels. However, for battery swapping a standard is more complex, since it is connected to the truck manufacturing companies' business model. Battery swapping can imply a decoupling between ownership of the battery and vehicle where two competing company-manufactured trucks hypothetically are required to swap batteries with

each other. The interviewee by this discusses whether battery swapping is a technical hinder or rather an institutional hinder, where the truck manufacturers want to keep the battery, and knowledge inside of their own business. The truck manufacturing companies also have an interest in protecting their business against competitors which cause a problem for collaboration and standardization. Ultimately, the interviewee argued that battery swapping is unlikely to be introduced in Sweden unless the larger OEM:s in the market allow it or unless another competing actor emerges at scale, willing to introduce and drive the technology independently.

The interviewee believes that to accelerate the electrification of heavy transport, policymakers need to take a long-term approach to policy design to create favorable conditions for development. According to the interviewee, policymakers should remain open-minded towards technology development and be receptive to shifts in the environment of HDEV. Specifically, the interviewee suggests that investment support for vehicle and charging infrastructure is crucial, at least in the beginning to accelerate the transition. Additionally, the interviewee emphasizes the importance of collaboration between various actors, including truck manufacturers, charging infrastructure providers, and logistics companies, to further accelerate the electrification of heavy transport.

Lastly, the interviewee discussed how to upscale electrified heavy transports. The interviewee believes that the challenges faced for small-scale electrification are vastly different from those faced during large-scale electrification. One significant challenge that arises during large-scale electrification is the impact on the power grid. When a large number of charging loads are connected to the grid simultaneously, the capacity in the power system becomes a limiting factor. The interviewee suggests that to tackle this issue, it is necessary to extend the grid capacity, and it is also crucial to involve electricity grid companies as important actors in large-scale electrification efforts.

5.3.2 Interviewee II

The interviewee argues that the biggest challenge for large-scale electrification of HDVs is the underestimated issue of energy supply. Electrification is meaningless if there is no functioning value chain of renewable energy supply in production, distribution, and use.

The interviewee also reflects on how charging impacts the electricity grid. The capacity of the electricity grid is insufficient to power an electrified heavy-duty fleet. To solve that problem, external energy storage batteries can help balance charging loads and supply vehicles with energy. However, the interviewee views this solution as an emergency solution. Battery swapping, in contrast, is a solution that involves external battery storage and the possibility to charge flexibly, but also provides a system where charging time is reduced. Battery swapping is an all-in-one system solution to reduce grid impact and increase Charging time.

This means that the batteries do not have to be as large as the electric trucks developed today with a battery capacity of around 500 kWh. The total installed battery capacity can be reduced. A reduced battery capacity reduces battery cost, and vehicle weight, and improves the load capacity of the vehicle. These are positive side effects of the reduced charging downtime, which is reduced from approximately two hours to about five minutes.

The interviewee has reflections on the scalability of different charging solutions and argues that battery swapping is easily scaled up. Cable charging, on the other hand, is challenging to scale up. Heavy trucks have large batteries and relatively long charging times. Charging a small number of vehicles with cables is feasible; however, large-scale electrification will result in large challenges in finding physical space for charging. The interviewee means that there is no physical space for large charging stations allowing the fleet to charge for hours. The interviewee also emphasizes that the capacity in the grid for the fleet to charge with fast chargers is insufficient as well. The interviewee argues that scaling up battery swapping is simple while scaling up cable charging faces large challenges.

Another perspective that the interviewee reflects on is that there are a lot of challenges with standardization for charging infrastructure development. Currently, different companies are developing different solutions in terms of sockets, placement of charging outlets, etc., to maintain their competitiveness on the market. The interviewee means that the charging device itself is not a demand for the customer. The customer only demands charging. However, companies compete with technologies and try to tie their

customers to their own developed techniques. The interviewee means that it is important that actors in the value chain agree on technologies for efficient development. There is a need for agreement between vehicle suppliers, battery suppliers, charging equipment, and all components in the value chain. To enable these agreements, political interaction, and commitment are crucial.

In the interview with interviewee II, many parallels and comparisons with the Chinese charging infrastructure development are made. In China, roughly half of the fleet that is presently produced is equipped with swappable batteries as a complement to cable charging, and battery swapping is an established charging technology. The interviewee means that large Swedish actors on the vehicle production side are skeptical of the battery swapping development due to their well-developed combustion engine trucks and the embeddedness in the conventional systems. However, the interviewee is certain that battery swapping will come to the Swedish market when actors with the technique are introduced.

Finally, the interviewee reflects on the challenges with battery swapping and emphasizes that it's not a question about technique. The technical aspects are already solved, and the challenge is how to create a competitive business model. In the interviewee's research, four dimensions are identified to describe the circumstances for electrification: technological readiness, political readiness, societal readiness, and economic readiness. The interviewee emphasizes that countries with well-developed political readiness have reached the largest scale of electrification. The electrification and development of charging infrastructure are not solely driven by companies, and there is a need for larger political responsibility in Sweden. Furthermore, when viewed from an international perspective, long-haul freight will require extensive political responsibility and international agreements for the development of charging infrastructure.

5.4 Sensitivity analysis

In the sensitivity analysis, different parameters will be altered to visualize different possible scenarios for future development. The different sensitivity analyses conducted are:

1. **Increased electricity costs:** since the prices on the electricity trade market during the year 2022 were significantly higher than normal, historically. A potential scenario could be that higher prices are seen in the future, therefore a sensitivity analysis with increased electricity costs is conducted.
2. **Future scenario for battery cost:** according to the presented forecasts, it is expected that the investment cost for the external battery will decrease. Therefore, a scenario with decreased battery cost is used for a sensitivity analysis.
3. **Increased electricity costs and future scenario for battery cost:** a scenario where both increased electricity costs and decreased external battery cost occur.
4. **Different external battery dimensions:** battery dimensions ranging from 2.7 MWh to 8.1 MWh are implemented.

Since the costs concerning battery swapping are on a theoretical level this sensitivity analysis is comparing DC-fast charging to DC-fast charging with external battery.

5.4.1 Increased electricity costs

In this section, a sensitivity analysis is applied as a scenario of increased electricity prices. The electricity prices that are used in this analysis are electricity trade prices for the year 2022 only. Table 5.3 shows the parameters for electricity trade costs during 2022. The yearly electricity costs are calculated in the same way as in section 4.4, but the cost parameters in Table 5.3 are applied instead of the cost parameters using the average electricity trade price from 2019-2022 in Table 4.8.

Table 5.3: Parameters for electricity trade costs during 2022 (Nord Pool 2023).

	2022
Yearly mean [SEK/kWh]	1 379
Standard deviation [SEK/kWh]	1 374
Median [SEK/kWh]	994
Number of high-cost days	142
Number of low-cost days	223
Number of total days	365
High-cost price [SEK/kW]	3.10
Low-cost price [SEK/kWh]	0.87

Given the new cost, new results are obtained. In Table 5.4 the result for DC-fast charging is shown.

Table 5.4: Cost parameters DC-fast charging with increased electricity costs.

Parameters	UR 30%	UR 60%
Number of chargers [CCS 150 kW]	4	4
Peak usage [kW]	600	600
Utilization rate [%]	30	60
Daily charging time [h]	7.2	14.4
Electricity amount charged during 24h [kWh]	4 320	8 640
Yearly electricity usage [MWh]	1 576	3 154
Fixed charge [SEK/year]	28 800	28 800
Monthly effect fee [SEK/year]	194 400	194 400
High load fee [SEK/year]	165 000	165 000
Transfer fee peak price [SEK/year]	66 666	133 333
Transfer fee low price period [SEK/year]	80 788	161 577
Summary grid fees [SEK/year]	535 655	683 110
Yearly electricity trade cost [SEK/year], using high-cost hours	4 881 842	9 763 685
Yearly electricity trade cost [SEK/year], using low-cost hours	1 378 859	2 757 718
Yearly electricity cost [SEK/year], using high-cost hours	5 417 497	10 446 794
Yearly electricity cost [SEK/year], using low-cost hours	1 914 514	3 440 828
Electricity certificate & Energy tax [SEK/year]	668 563	1 337 126
Yearly electricity cost [SEK/year], using traffic distribution	4 056 402	7 640 746
Cost per MWh [SEK/MWh]	2 573	2 423

In Table 5.5 the result for DC-fast charging with external battery is shown.

In Figure 5.1 the yearly electricity costs with the average price are presented, as in section 4.4, and the yearly electricity costs with 2022 years prices. The blue column shows the savings between the two charging technologies when an external battery is introduced and different electricity prices are applied. In Figure 5.2 the same information can be found but with a utilization rate of 60%. As seen in the figures, the savings increase significantly for external battery in the scenario with increased electricity costs.

Since the electricity costs for battery swapping are assumed to be the same as for DC-fast charging with an external battery, as explained in section 4.4.5. Therefore, in this sensitivity analysis, the same assumption is considered. However, this study does not deepen the considerations for battery swapping when analyzing the quantifiable criteria.

5.4.2 Future scenario for battery cost

As presented in section 2.3.2 the prices on the VFR batteries are expected to decrease. According to International Renewable Energy Agency (2017) the investment cost for the year 2030 is expected to be 1228 SEK/kWh for the VRF battery. In this sensitivity analysis, the projected battery prices for 2030

Table 5.5: Cost parameters DC-fast charging with external battery and increased electricity costs.

Parameters	UR 30%	UR 60%
Number of chargers [CCS 150 kW]	4	4
Charging time [h]	7.2	14.4
Electricity amount charged during 24h [kWh]	4 320	8 640
Yearly electricity usage [MWh]	1 577	3 154
Fixed charge [SEK/year]	28 800	28 800
Monthly effect fee [SEK/year]	116 640	116 640
High load fee [SEK/year]	99 000	99 000
Transfer fee peak price [SEK/year]	60 726	121 451
Transfer fee low price period [SEK/year]	82 863	165 726
Summary grid fees [SEK/year]	388 029	531 617
Yearly electricity trade cost [SEK], using high-cost hours	4 881 842	9 763 685
Yearly electricity trade cost [SEK], using low-cost hours	1 378 859	2 757 718
Yearly electricity cost [SEK], using high-cost hours	5 269 871	10 295 302
Yearly electricity cost [SEK], using low-cost hours	1 766 888	3 289 335
Electricity certificate & Energy tax [SEK/year]	668 563	1 337 126
High-cost use [%]	58%	58%
Low-cost use [%]	42%	42%
Yearly electricity cost [SEK], using cost distribution	3 230 420	6 216 400
Cost per MWh [SEK/MWh]	2 049	1 971

Yearly electricity costs UR 30%

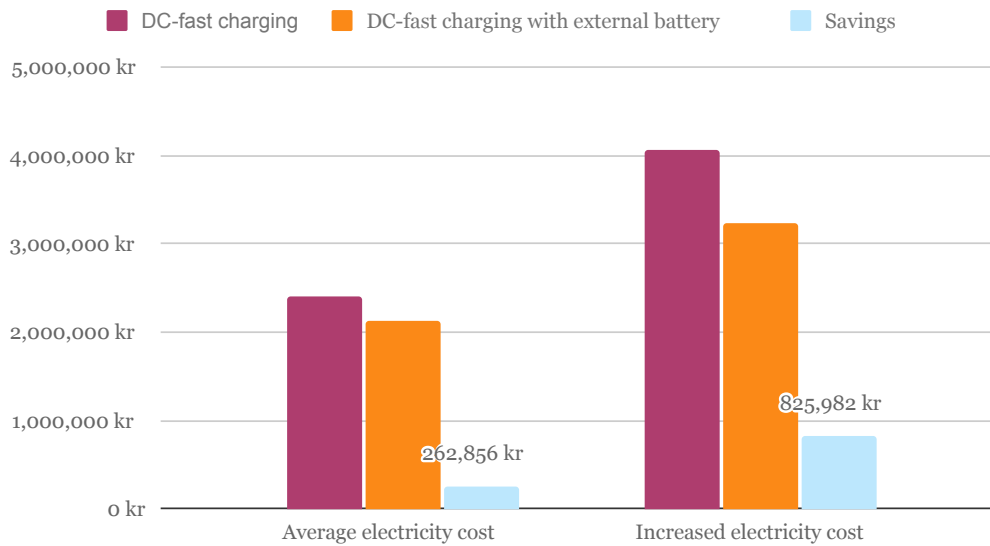


Figure 5.1: Overview of the yearly electricity costs for DC-fast charging with and without external battery and utilization rate 30%. Showing the savings using the two technologies.

are applied as 1228 SEK per kWh instead of the 2405 SEK per kWh as in the original case. Resulting in a battery cost of 3 015 494 SEK instead of 5 904 285 SEK as in the original case. The yearly electricity costs are calculated in the same way as in section 4.4.4 since no parameters concerning electricity costs are altered. The yearly electricity cost is the same as in section 4.4.4. A summary of the result for yearly electricity cost is shown in Table 5.6.

5.4.3 Increased electricity costs and future scenario for battery cost

In this section, a scenario where both the electricity costs are at a level of the year 2022 as in section 5.4.1 and the battery costs are projected as in section 5.4.2, is presented. The yearly electricity costs

Yearly electricity costs UR 60%

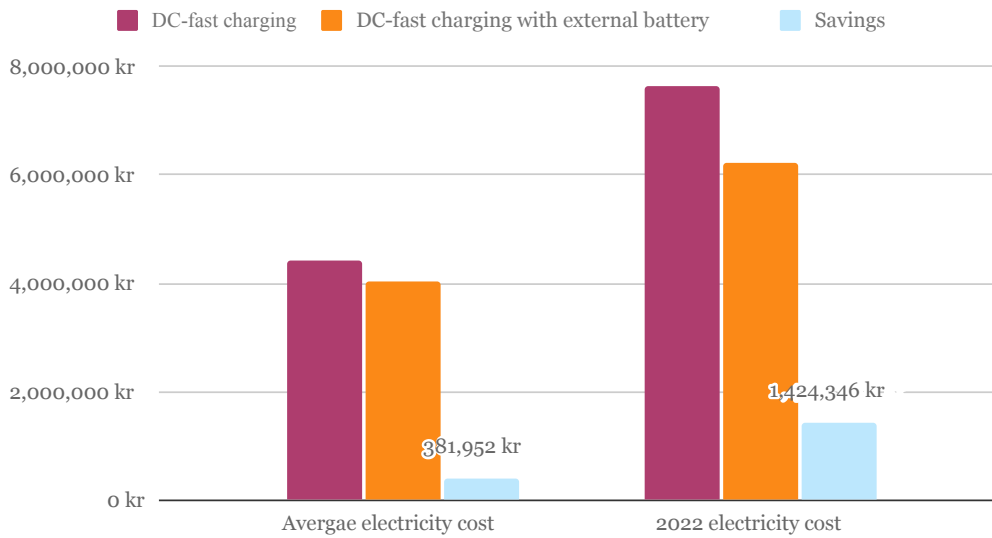


Figure 5.2: Overview of the yearly electricity costs for DC-fast charging with and without external battery and utilization rate 60%. The blue columns are showing the savings between the two technologies.

Table 5.6: Yearly electricity cost for DC-fast charging with external battery and decreased battery costs.

Parameters	UR 30%	UR 60%
Yearly electricity cost [SEK], using cost distribution	2 138 879	4 033 318
Cost per MWh [SEK/MWh]	1 356	1 279

are calculated as in section 5.4.1 but the investment cost for the solution is applied as in section 5.4.2. The yearly electricity cost does not differ from the sensitivity analysis in section 5.4.1 and the battery investment cost does not differ from the cost presented in section 5.4.2 therefore the only parameter that will result in new values is the ROI and pay-off time, which is presented in section 5.4.5, below.

5.4.4 Different external battery dimensions

A larger battery size than 2.5 MWh can potentially decrease the high-cost period electricity use. However, the larger the installed battery capacity the more load is needed for external battery charging, meaning that at a certain point, the installed capacity will not be smaller than in the solution without an external battery. Resulting in increased installation costs and grid fees but also reduced electricity trade costs. Continuously the climate impact can be reduced by a larger installed external battery. This is because the larger battery installed, the more electricity use can be moved from coal-condensing marginal generation to wind power marginal generation.

Battery sizes between 2.5 and 8.1 MWh are tested, where 2.5 MWh is the original case. Section 5.4.5 shows yearly electricity savings, battery cost, ROI, and pay-back time.

Below are load profiles for the different battery dimensions, presented. Commonly for all figures are that the energy use every hour is shown. Where the grey line shows charging demand, the purple line shows peak load (resulting installed capacity), the orange columns show the load grid to the battery, the red columns show the load from battery to vehicles, and the blue columns show the load from the grid to vehicles. Hours 8-21 are high-cost hours.

In Figure 5.3 installed capacity of 400 kW results in a battery size of 2.7 MWh visualized.

Load profile 400 kW installed capacity, 2.7 MWh battery size

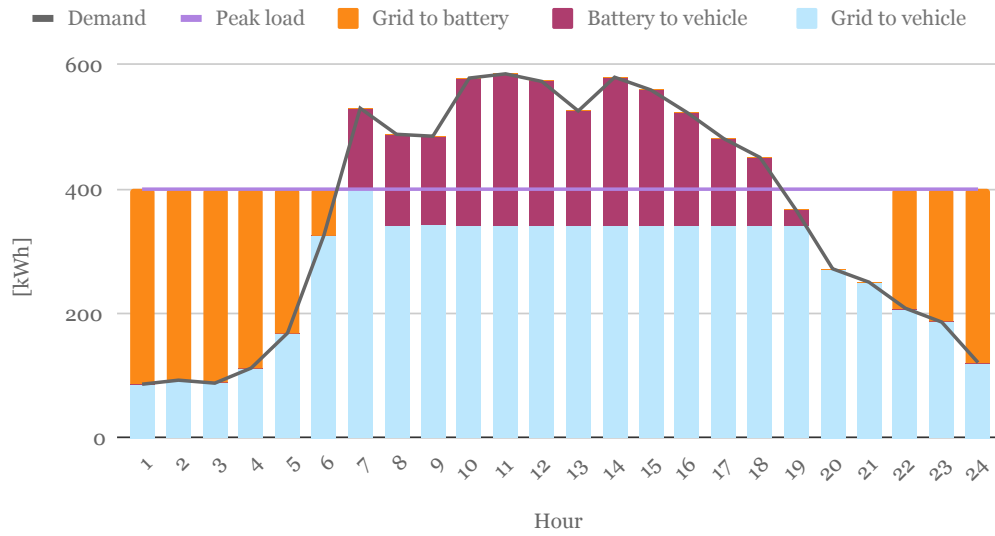


Figure 5.3: Load profile of charging station with external battery, and an installed capacity of 400 kW and utilization rate 60%.

In Figure 5.4 installed capacity of 500 kW results in a battery size of 3.7 MWh visualized.

Load profile 500 kW installed capacity, 3.7 MWh battery size

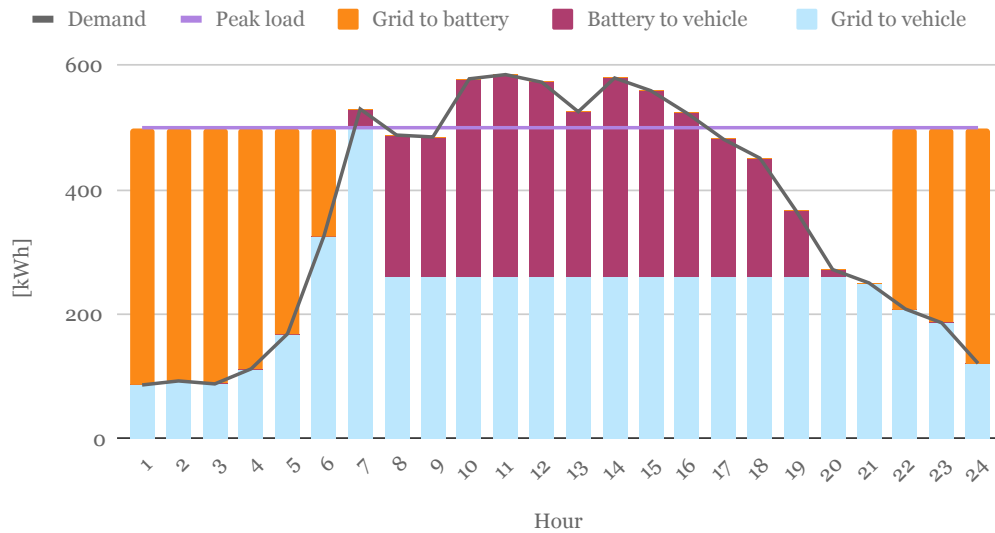


Figure 5.4: Load profile of charging station with external battery, and an installed capacity of 500 kW and utilization rate 60%.

In Figure 5.5 installed capacity of 600 kW results in a battery size of 4.9 MWh visualized. 600 kW is the same capacity as in the solution without external battery. Here high-cost charging can be avoided. However, the advantage of a smaller installed grid capacity is no longer present.

Load profile 600 kW installed capacity, 4.9 MWh battery size

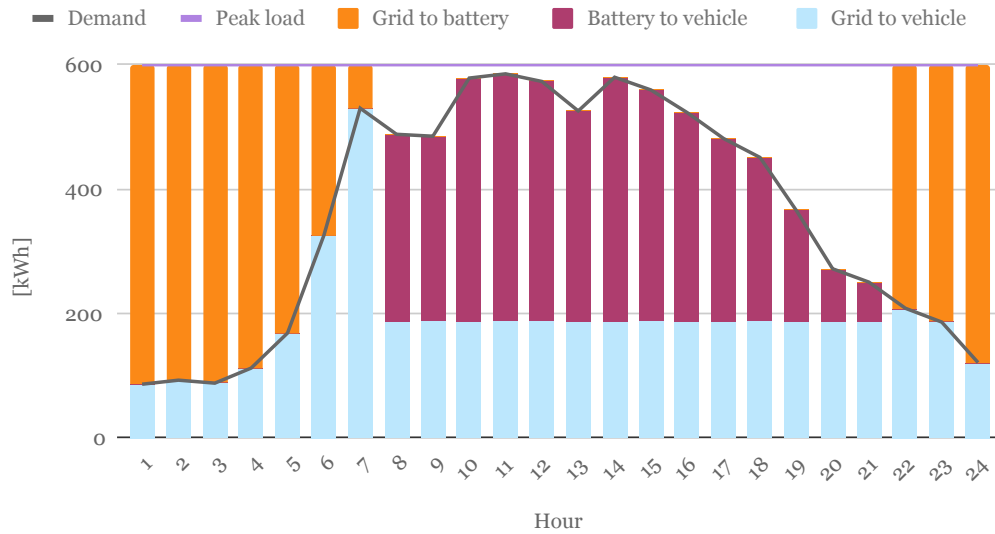


Figure 5.5: Load profile of charging station with external battery, and an installed capacity of 600 kW and utilization rate 60%.

In Figure 5.6 installed capacity of 700 kW results in a battery size of 6.1 MWh visualized.

Load profile 700kW installed capacity, 6.1 MWh battery size

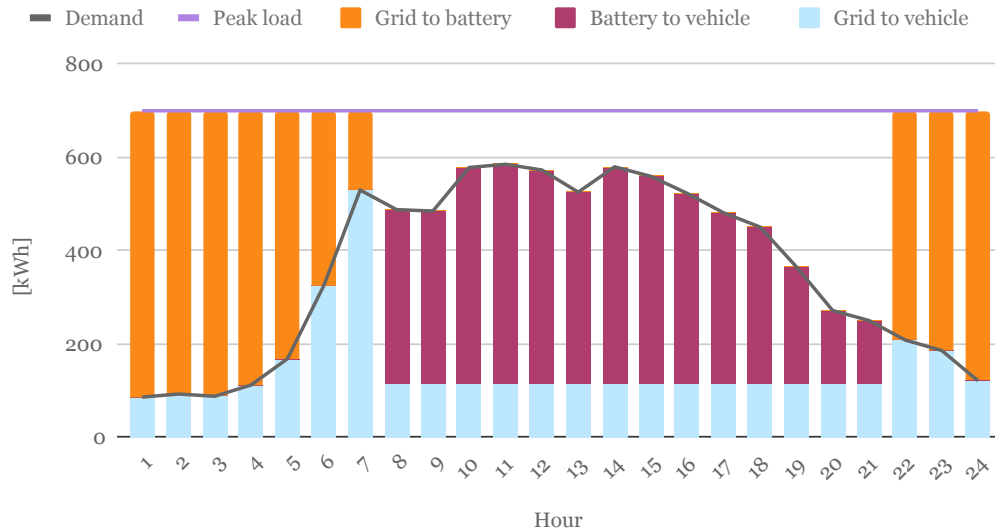


Figure 5.6: Load profile of charging station with external battery, and an installed capacity of 700 kW and utilization rate 60%.

In Figure 5.7 installed capacity of 864 kW results in a battery size of 8.1 MWh visualized. This is the largest dimension of the battery that is of interest. This is because all electricity use during high-cost hours is avoided.

In Figure 5.8 the division between grid fees and electricity trade costs for each battery size and both utilization rates are shown. It can be seen that the trade costs decrease due to a larger battery and that

the grid fees increase due to a larger installed grid capacity. However, the total electricity costs decrease with a larger battery. The higher utilization rate results in a more efficient cost decrease with a larger battery, as seen in Figure 5.8.

Electricity trade costs, grid fees and yearly electricity costs

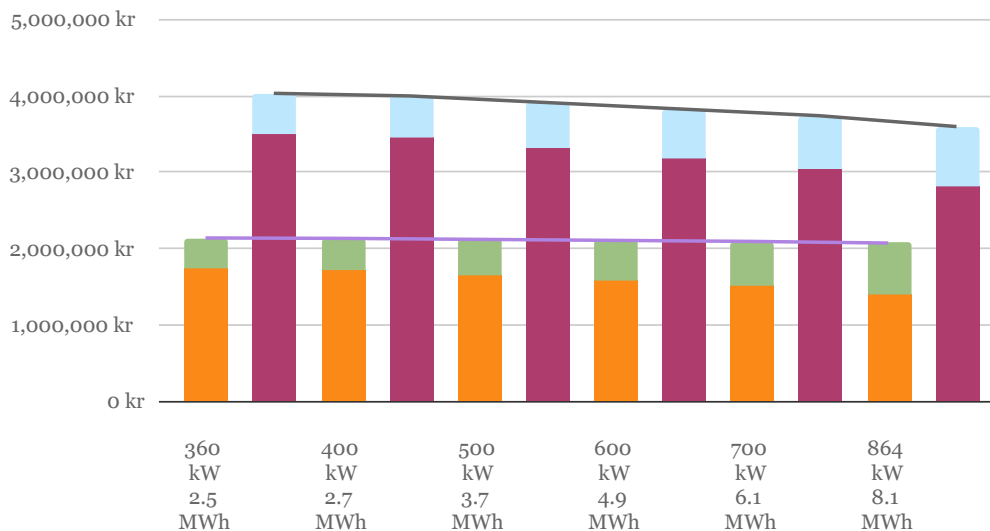


Figure 5.8: The yearly electricity trade costs, grid fees, and total costs are visualized for utilization rates 30% and 60%. The orange and green columns refer to a utilization rate of 30%, purple, and blue columns refer to utilization rate of 60%. The orange columns are electricity trade costs, the green columns are grid fees, the purple columns are electricity trade costs, the blue columns are grid fees.

The climate impact is calculated as in section 4.5, in Figure 5.9 the CO₂eq emissions from DC-fast charging and DC-fast charging with external battery of different sizes is shown. The emissions range from 2360 tonne/year to 38 tonne/year. The emissions are reduced due to less energy used during coal condensing marginal periods. For the battery capacity of 8.1 MWh, 38 tonnes of CO₂eq per year are emitted. During those conditions, only wind-power-generated energy is used. The result shows that the energy heritage is decisive for the amount of emissions.

Emissions from electricity use UR 60% (tonneCO₂eq/year)

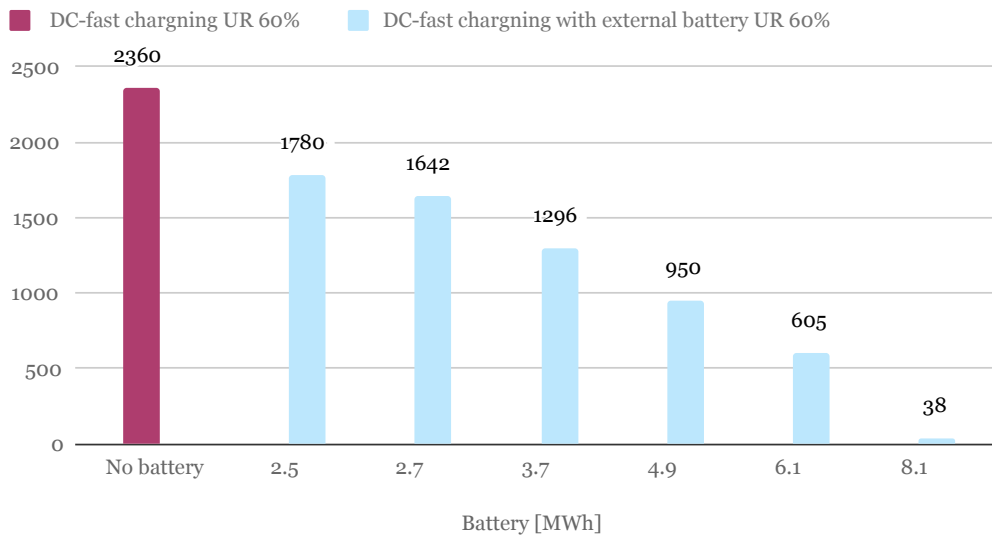


Figure 5.9: Tonne CO₂eq per year for different battery sizes. The purple staple visualize the emissions from DC-fast charging without an external battery, the blue staples visualize the emissions from the DC-fast charging solutions with different sizing of the external battery.

5.4.5 Summary of results, yearly electricity costs

In the following section, a summary of the applied sensitivity analysis is presented. In Table 5.7 the yearly savings comparing DC-fast charging to DC-fast charging with external battery are shown. Additionally, the investment cost, ROI, and pay-back time are presented for the scenarios in the sensitivity analysis and the different utilization rates. As presented, all scenarios strengthen the incentives for an external battery solution. For all scenarios the pay-back time is shorter than the technical lifetime of the external battery (20 years). However, the increased electricity costs affect the business case more than the decreased battery costs. When both scenarios occur at the same time the business case is the strongest, resulting in a pay-back time on respectively 3.4 and 2.0 years, compared to the original case the numbers were respectively 21.7 and 15.0 years.

Table 5.7: Yearly electricity savings, battery cost, ROI, and pay-back time.

Scenario	Increased elec- tricity costs	Future scenario for battery cost	Increased elec- tricity costs and future scenario for battery cost
Yearly electricity savings UR 30% [SEK/year]	825 982	262 856	825 982
Yearly electricity savings UR 60% [SEK/year]	1 424 346	381 952	1 424 346
Investment cost [SEK]	5 904 287	2 824 294	2 824 294
ROI UR 30% [%]	14.5	9.3	29.2
ROI UR 60% [%]	24.9	13.5	50.4
Pay-back time UR 30% [years]	6.9	10.7	3.4
Pay-back time UR 60% [years]	4.0	7.4	2.0

The results from the sensitivity analysis which involved different dimensions of the external battery can be found in Table 5.8, the battery capacity ranges from 2.5 to 8.1 MWh. Installed capacity, yearly savings, investment cost, ROI, and payback time are presented. As seen the pay-back times increase with larger battery capacity, due to the larger investment cost that increases faster than the savings resulting from external battery storage.

Load profile 864kW installed capacity, 8.1 MWh battery size

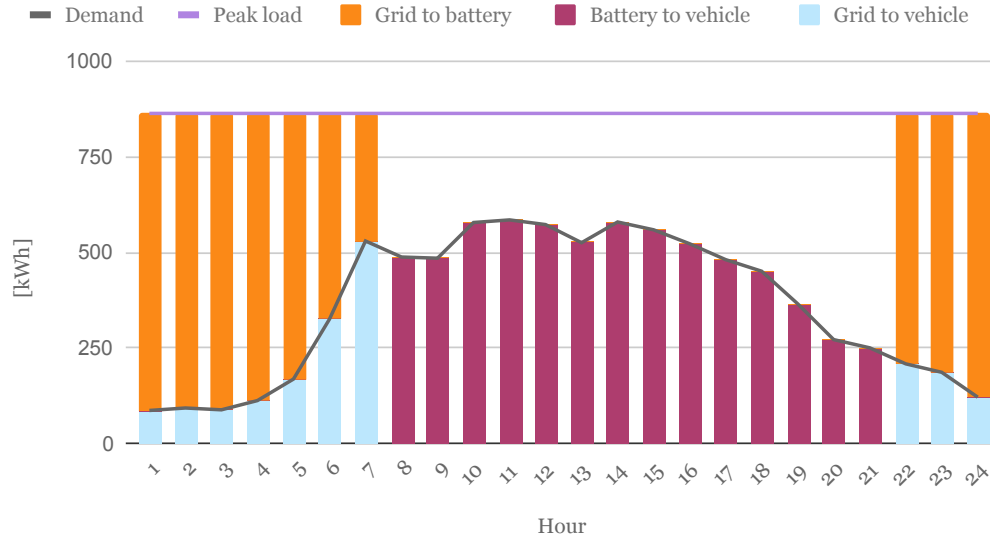


Figure 5.7: Load profile of charging station with external battery, and an installed capacity of 864 kW and utilization rate 60%.

Table 5.8: Installed capacity, battery capacity, and battery cost.

Battery size [MWh]	2.5	2.7	3.7	4.9	6.1	8.1
Installed capacity [kW]	360	400	500	600	700	864
Yearly electricity savings UR 30% [SEK/year]	262 856	268 161	281 423	294 685	307 948	329 698
Yearly electricity savings UR 60% [SEK/year]	381 952	416 522	502 947	589 371	675 795	817 531
Investment cost [SEK]	5 713 087	6 197 445	8 832 369	11 769 010	14 692 482	19 586 976
ROI UR 30% [%]	4.6	4.3	3.2	2.5	2.1	1.7
ROI UR 60% [%]	6.7	6.7	5.7	5.0	4.6	4.2
Pay-back time UR 30% [years]	21.7	23.1	31.4	39.9	47.7	59.4
Pay-back time UR 60% [years]	15.0	14.9	17.6	20.0	21.7	24.4

In Table 5.9 a summary of the different costs per charged MWh for all scenarios is shown. As presented the highest cost per charged MWh is the scenario without external battery storage and with increased electricity costs. The lowest cost per charger MWh, is the scenario with the largest tested battery of 8.1 MWh installed, resulting in that all high-cost energy use can be avoided. However, as presented in Table 5.8 the savings are not enough to pay off the investment in required pace to make this solution profitable, with current energy and battery costs.

Table 5.9: Summary of cost per charged MWh.

Cost per charged MWh [SEK]	Utilization rate 30%	Utilization rate 60%
DC-fast charging (original case)	1 523	1 400
DC-fast charging with external battery (original case)	1 356	1 279
DC-fast charging (Increased electricity prices)	2 573	2 423
DC-fast charging with external battery (Increased electricity prices)	2 049	1 971
DC-fast charging with external battery (2.7 MWh battery)	1 353	1 268
DC-fast charging with external battery (3.7 MWh battery)	1 345	1 241
DC-fast charging with external battery (4.9 MWh battery)	1 336	1 213
DC-fast charging with external battery (6.1 MWh battery)	1 328	1 186
DC-fast charging with external battery (8.1 MWh battery)	1 314	1 141

Below the multi-criteria analysis is presented for each sensitivity analysis. In Table 5.1 the MCA for the original case can be found.

The MCA for the scenario with increased electricity cost can be found in Table 5.10, for this scenario the yearly energy costs are higher, resulting in DC-fast charging and battery swapping performing stronger then DC-fast charging compared to the original case. When higher energy costs are applied the difference between the charging solutions with external battery advantage and the charging solution without is more significant. Resulting in a lower score for DC-fast charging.

Table 5.10: Result from increased electricity costs.

Criteria/Technology	DC-fast charging	DC-fast charging with external battery	Battery swapping
Investment	1	0.4	0.6
Charging time	0.04	0.04	1
Yearly electricity cost	0.8	1	1
Climate impact	0.8	1	1

The MCA for future scenario of battery cost can be found in Table 5.11. In this scenario, the investment cost for DC-fast charging is the criterion that differ. Since the cost for external battery is reduced by almost 50%, DC-fast charging with external battery scores higher then in the original case. However DC-fast charging and battery swapping, still have lower investment cost, comparing.

Table 5.11: Result from future scenario for battery cost.

Criteria/Technology	DC-fast charging	DC-fast charging with external battery	Battery swapping
Investment	1	0.5	0.6
Charging time	0.04	0.04	1
Yearly electricity cost	0.9	1	1
Climate impact	0.8	1	1

The MCA for both scenarios can be found in Table 5.12. In this scenario both yearly electricity cost and investment cost are affected, as described in the two scenarios above. In this scenario DC-fast charging is strengthened in both investment and yearly electricity cost, and battery swapping is strengthened by yearly electricity cost solely.

Table 5.12: Result from increased electricity costs and future scenario for battery cost.

Criteria/Technology	DC-fast charging	DC-fast charging with external battery	Battery swapping
Investment	1	0.5	0.6
Charging time	0.04	0.04	1
Yearly electricity cost	0.8	1	1
Climate impact	0.8	1	1

6 Discussion

The following section will include discussions related to the presented results of the thesis. Additionally, more specific discussions about the charging technologies and the determined criteria are included. A methodology discussion is included, where validation, reliability, and generalizability are considered.

6.1 General discussion about result from multi-criteria analysis

In section 5.1 the overall results can be found, as Table 5.1 presents how the three charging technologies perform compared to the quantifiable criteria. The scores related to the criteria are supposed to indicate how the charging technologies are performing in comparison to each other. Given the fact that it can be difficult to make generalized assumptions, as there are several factors affecting the cause of a charging technology that is suitable to adopt.

DC-fast charging scores the highest for *investment*, this is because of the low investment cost compared to the two remaining technologies. The investment cost for DC-fast charging with an external battery includes both the investment cost for the charging station with an addition of the external battery. As the investment is calculated with the prices for the current year (2023), this includes a high investment cost for the external battery. Although DC-fast charging with external battery scores the lowest for investment cost it can be argued that it can be worth investing even if there is a high investment cost, when considering other factors.

Considering the criterion *charging time*, Table 5.1 shows that battery swapping scores are, by far, higher than the DC alternatives. This is because the charging downtime for battery swapping refers to the swapping time of a battery as presented in section 4.3. However, it is noteworthy when assessing the technologies, how important the charging downtime is considered. For instance, if downtime is a limiting factor, battery swapping might be very advantageous. If the charging downtime on the other hand is not desired, in a case where the potential driver of the vehicle anyway is having break time the short downtime might not be an advantage. As argued by Interviewee I (2023), the "logic of logistics", where long charging time could conflict with future electrified and efficient transport systems. In such cases, the charging time is important to reduce or to take advantage of the idle period and possibly conduct other assignments. This makes the charging time a parameter that might vary in importance, considerably depending on the type of transport using the charging stations. This could support a scenario where different charging solutions are suitable for different locations, such as public stations or depot charging stations. For instance, battery swapping would be suitable for public charging stations, but not for "during break" charging. Logistics companies have low margins and therefore charging downtime can be crucial. During mid-shift charging, high-power charging is needed to accelerate the adoption of HDEV (Borlaug et al. 2022). Borlaug et al. (ibid.) suggest that charging at megawatt level is needed to meet the required charging speed for mid-shift charging. In addition, the driving range of EVs is a more limiting factor than the range of ICE trucks. Unlike an HDEV, an ICE truck can refuel rapidly at any fuel station (Abid et al. 2022). Accordingly, charging time is an important factor since the time required to recharge electric vehicles impacts the total travel time (ibid.).

The results presented in Table 5.1 show an equal score for DC-fast charging with an external battery and battery swapping for the criterion *yearly electricity cost*. The reason is that both of the charging technologies are considered to possess the same possibilities to manage the charging load. The underlying cause for the lower score for yearly electricity cost for DC-fast charging is that it does not include any possibilities of load balancing. The result implies increased electricity costs as presented in section 4.4.3.

Furthermore, the criterion *climate impact* in Table 5.1 scores higher for the solutions with external energy storage capacity, meaning DC-fast charging with external battery and battery swapping. This is due to the ability to manage the load and use more energy during specific time periods with less fossil-intensive energy generation on the margin. Additionally, as presented in Figure 5.9 the impact from CO₂eq emissions can be even more reduced if a larger battery capacity is installed and less energy can be used during coal condensing periods in the energy landscape. It is important to note that the potential reduced

climate impact from shifting from ICE trucks to HDEV is only achievable if the energy generation source contains a low amount of fossil fuels. This since a considerable amount of the emissions that the HDEV is accountable for are related to electricity production (Sen et al. 2017). As presented in section 2.1.3 the more integrated the European energy system becomes, the gas turbines from natural gas could be on the margin. This means that even if the energy mix in Sweden becomes less fossil-intensive, fossil-intensive energy generated somewhere else is still on the margin. Resulting in large savings in CO₂eq emission from introducing external batteries. However, to tackle climate change by reducing climate emissions it is crucial that the energy generation is fossil-neutral for HDEV to contribute to sustainable development.

6.2 Advantages, challenges, and business considerations for Battery Swapping

Battery swapping can be considered a promising alternative for charging technology, as it overcomes hinders that DC charging retains. Mao et al. (2023) argue that the shortened charging time, the subscription concept of the battery swapping service, and the potential of storing energy in the station as three main advantages for HDEVs using battery swapping compared to cable charging. The remarkably short swapping time is an advantage and the possibility to adopt flexible charging patterns to manage peaks and store energy. Where the short swapping time and the energy storage possibility are shown as advantages compared to cable charging in this study, in the presented MCA in Table 5.1. The adoption of battery swapping in the APAC region shows that it is a successful charging alternative, as mentioned in section 2.3.3. J. L. Liu et al. (2021) support the fact that battery swapping is a favorable alternative for HDEVs and emphasizes that the charging solutions are more suitable for heavy vehicles than for passenger vehicles. The reason for this is that it is easier to integrate a swappable battery pack in an HDEV, due to factors such as their size and the design of the vehicle (ibid.). As Interviewee I (2023) emphasizes, transportation vehicles are not predictable in terms of driving distance, which can vary from day to day. This further supports the option of adopting a subscription model for battery swapping, where the range differs and it is possible to use a battery suitable for the customary route. Furthermore, J. L. Liu et al. (2021) argue that it is easier to adopt battery swapping for HDEV due to the fact that heavy freight focuses upon function and operations rather than the design and brand of the vehicle, in comparison to passenger vehicles.

Although battery swapping seems promising the charging solution brings implications. The charging technology's main adoption is in Asian countries. As discovered by this study there are difficulties finding suppliers that deliver to the European market. Similarly, it will demand significant changes and action for a local supplier or manufacturer to provide battery swapping as a charging solution. This marks both the charging station and the vehicles to be appropriate for battery swapping. Correspondingly, the current European trucks are not designed to suit the battery-swapping solution. It requires significant changes in the vehicles and infrastructure around them, to be suitable for the swapping process. Another aspect for arguing if battery swapping will be utilized in a Swedish context is for the charging infrastructure to be deployed before or if it is a necessity to implement the battery swapping compatible vehicles first. It is a question about what comes first, the chicken or the egg? Is it possible to introduce battery swapping vehicles in the Swedish market before there are extensive battery swapping stations? A study by J. L. Liu et al. (ibid.) emphasizes that the utilization rate for a battery swapping station needs to be more than 50% to be profitable. For this reason, it will be difficult for companies providing battery swapping stations to implement their charging solution in an area or region where there are no operating compatible vehicles. Whereas, from the perspective of the truck owner, it is difficult to invest in battery swapping vehicles when there are no swapping stations available. It can be discussed by the fact that the vehicles compatible with battery swapping, also are compatible with cable charging (as mentioned in section 2.3.3). Although this enables the possibility for the vehicles to be charged in DC-fast charging stations, the additional cost will need to be taken into consideration. Furthermore, as discussed by Interviewee I (2023), the deployment of battery swapping is challenged by institutional hindrances. Where battery swapping requires actors to share information to have vehicles and stations compatible with each other. Confidential information and conflicting interests could be hindering this development. This is supported by the arguments from Interviewee II (2023), where the interviewee argues that the challenges with battery swapping and is not a question about technical aspects. Interviewee II (ibid.) means that the technical aspects are solved and that the challenging part is how to create a competitive business model.

6.3 Investment implications and technology maturity

The breakdown of the investment considered in this study involves cost posts regarding each individual charging system, as presented in Table 4.1. The breakdown is general, not considering special details for the individual charging systems. The substation has varying costs depending on the installed capacity of the charging station, which is a parameter that affects the investment cost depending on which charging solution is installed.

Another component that will differ among the charging systems is the cables, where there is a different need for both length, quality, and capacity of the cables dependent on the requirements. The charging stations considered in this study involve a high-powered system which results in a need for thicker cables to sufficiently transfer the required power. Although cables are an essential part of the systems and the cost post referring to cables can differ among the charging technologies, this is not considered in the study. Moreover, some of the cost posts are considered to be equal for the three charging systems. Which includes; foundation, refuge, and electrical installation. The delimitation is decided with the assumption that the differences between these cost posts are negligible in relation to the total investment, however, this affects the reliability of the result.

DC-fast charging with external battery is highly affected by the aspect of high investment costs when referring to scalability. Where it can be assumed that the external battery is dimensioned for the initial investment. To be able to up-scale such a station would require a change of the dimensions for the external battery, or investment in additional battery capacity. This makes an up-scaling of the charging station an expensive investment, as the external battery still is an expensive technology.

Another factor to take into consideration when investigating *investment costs* is the maturity of the technologies. As the market for HDEVs is nascent the charging technologies can be considered immature, as an implication of the low sales of HDEVs (International Energy Agency 2023). Immature technologies tend to be more expensive. As follows, the estimated price trends for the vanadium redox flow battery, as in section 4.2. Where the price for BESS at the current state is high, but predicted to fall as the technologies mature. Although VRFB is considered one of the most mature batteries deployed on the scale of MW power level and is predicted to decrease in price (IEA 2023). Furthermore, it is expected that new battery technologies will enter the market of BESS. Such supply increase would be beneficial for the charging infrastructure, and decrease the investment cost for energy storage systems.

Likewise, the decrease in price in relation to the maturity level of the technology could be associated with the total investment costs for the charging technologies. Where battery swapping is solely from Asian suppliers today, if battery swapping is adopted in a global context the investment cost could decrease. Where more suppliers would enter the market of both battery swapping stations and vehicles. In contrast, DC-fast charging which can be considered to represent a higher level of maturity, in comparison with battery swapping. This could imply that the price curve for DC-fast charging stations reflects a mature technology, whereas the price curve of battery swapping is more likely to reflect an immature technology. As Interviewee I (2023) argues, the initial investment is extensive, although the investment and implementation will, in the long run, be profitable. This can support the fact that a costly investment today can be beneficial.

6.4 Managing energy costs and grid limitations for HDEV charging

Energy security of supply is an increasingly important issue while the transition towards renewable energy sources takes place. Where the reliance on fossil fuels decreases and the reliance on energy sources such as electricity produced from intermittent sources increases.

6.4.1 Opportunities and challenges regarding the energy system

During the year 2022, the energy landscape in Sweden experienced higher and more volatile electricity prices than historically. There are several reasons explaining this. The Swedish electricity grid is limited by transmission capacity and even though electricity generation, from wind and hydro sources, is sufficient, enough power cannot be transported to required areas, at all times (Energimarknadsinspektionen 2022).

Henceforth, a large installed wind power generation can enable fossil-free, cost-efficient electricity, yet changes in supply from wind power production can result in volatile prices (Energimarknadsinspektionen 2022). As presented in section 2.1 in Figure 2.1 if generation from wind is rapidly interrupted, in case of reduced wind strength, a new energy source with higher marginal cost carries to supply the energy demand. Additionally, the Swedish energy market is interconnected with the European market and if there is a lack of wind in large parts of Europe the market prices rapidly increase (ibid.), resulting in the Swedish energy costs are dependent on the European context. Since autumn 2021 natural gas prices have been higher than normal, resulting in generally increased energy prices in Europe (ibid.).

As explained in section 2.1 the energy prices vary a lot depending on the balance between supply and demand. During high-demand periods more expensive electricity generation facilities are required to generate power, resulting in higher volatile prices. Hence, a strategy to reduce energy costs for energy end users is to react to the prices by managing electricity use in less expensive periods. This reaction could, at a large scale, also help to even out the general demand in the energy system which has positive effects such as lower costs, stability, and less fossil-intensive electricity generation.

In this study two of the charging technologies can incorporate strategies that can handle the issues described above. Both DC-fast charging with external battery and battery swapping, are technologies that can even out the charging demand to a more stable demand. In Figure 4.3 the load demand for charging without these technologies is shown. Visible is that the demand is varying during the day and that the peak demand occurs during the general peak period in the electricity system. This results in high, volatile prices for energy purchases. In comparison, DC-fast charging with external battery and battery swapping enables an even power demand of 360 kW throughout every hour of the day.

Additionally, costs for energy purchase consists of both grid costs and electricity trade cost. Above discussed are the electricity trade costs, which increase during high-load periods, likewise the grid costs increase. As presented 4.7 there is a higher cost for transmission during peak price periods. Moreover, the cost for installed capacity, meaning the peak use, is also charged per kW, as seen in Table 4.7. Comparing the three solutions from these costs DC-fast charging without any load management has the largest grid fees of all solutions. In the case study, all three systems use the same electricity amount, the difference is when the energy is transmitted.

In connection to the grid costs, where a larger installed capacity results in larger fees for transmission, there is also another aspect to concern. As mentioned in section 2.1.1 there is a lack of capacity for transmission in many parts of the Swedish electricity system. This has led to company establishments being stalled due to the shortage (Wiesner et al. 2019). A scenario where the shortage of capacity stops a potential establishment of a charging station is a reality in several parts of Sweden. In such cases, solutions around BESS or flexibility might be a condition to consider, regardless of the profitability in the short term. However, a lot of responsibility lies on the grid owners at the location. In Sweden, there is a natural monopoly on grid areas, which interplay on the development and pace that the grid capacity is built out in (ibid.). The grid owners are obliged to connect new users to the grid. Nonetheless, they are allowed to decline connection if it would risk the supply to the current costumers (ibid.). This can lead to a hindrance to the expansion of company activities, and climate change adaptation by electrification. The grid-owning companies have strong requirements for connecting new customers but the delineation of where the responsibility reaches and to what extent they are allowed to decline connection has not been tested (ibid.). To tackle the problem Wiesner et al. (ibid.) emphasize that collaboration between different actors is important. This collaboration could refer to the grid owners and the energy users where flexibility and adaptation can help to relieve the pressure on the grid. For instance, an HDEV public charging provider can create incentives for their customers to encourage off-peak charging or to use BESS for balancing energy use. In return, the grid owners could provide flexibility to a larger extent than present. One idea could be to provide dynamic connections. For instance, during night when electricity trade costs usually are lower and the grid is not heavily loaded the grid owners could provide diversified connections, meaning that a customer is allowed to use a larger power during night time than during day time. If so, a customer would have the incentive to manage loads to those time periods, and the overall energy use could be more evenly distributed. It would also, partly, handle a situation where customers are declined connection. A result could be better utilization of resources and a less pressured grid.

6.4.2 External battery storage opportunities

There are several arguments supporting investment in external battery storage as a complement to cable fast charging. Yet, the investment cost for external battery storage is very high compared to possible decreased costs. Comparing the yearly electricity costs for DC-fast charging and DC-fast charging with external battery in the original case in Table 4.14 the yearly savings are 263 000 SEK and 382 000 SEK for the different utilization rates and the increased cost for investment are 5 700 000. Given this, the pay-back time is 21.7 and 15 years respectively for the two utilization rates and the ROI is 4.6% and 6.7%. Given the lifetime of the battery of approximately 20 years as presented in Table 4.4, this investment has a high risk of not being profitable. With current circumstances, it is important to emphasize that flexibility in charging patterns and flexible load demands are important enablers for managing energy costs and relieving the pressure from the electricity system. The global EV outlook of 2023 by International Energy Agency (2023) suggests that the opportunity for off-shift charging will reduce the charging costs, where the economics for HDEVs are improved as a consequence. As mentioned in section 2.2.2, there are opportunities to manipulate the charging patterns to help increase the flexibility of the power system. To leverage this there is a need for controlled charging, as mentioned in section 2.2.2. Borlaug et al. (2022) discusses that scheduling the charging to off-shift contributes to increased operating efficiency and lower charging costs.

However, it is likely that BESS decrease in cost as presented in section 4.2. It is also a possible scenario that electricity trade costs become higher and more volatile. In those cases the incentives for an external battery solution to manage electricity load rise. Figure 6.1 summarizes earlier presented results and shows the pay-back time in relation to ROI for the original case and the sensitivity analysis. In the figure, it is visible that the incentives for external battery storage increase significantly in cases of higher electricity costs or decreased investment costs. If both scenarios occur simultaneously the pay-back time is only two years for the utilization rate of 60%.

Pay-back time and ROI for the sensitivity cases and utilization rates

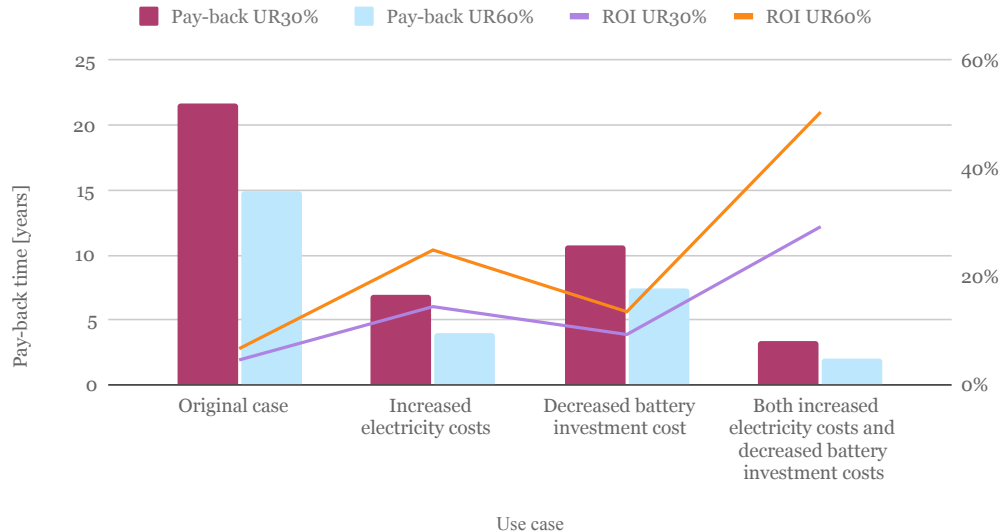


Figure 6.1: Pay-back time and ROI for the original case, the case with increased electricity costs, the case with decreased battery costs, and the case with both increased electricity costs and decreased battery costs. Pay-back values refer to the left axis and ROI values refer to the right axis.

Continuously, in section 5.4.4 different sizes of batteries are tested. Since the investment cost is high and the energy costs are not enough high to reach profitability it is seen that the investment in larger BESS storage does not gather enough savings in energy costs to increase profitability. The data presented in Table 5.8 shows that the pay-back time for installing a larger battery increases substantially, to time periods that are much longer than the battery's technical lifetime of approximately 20 years. Nevertheless, it should be noted that larger battery capacity enables a more effective shift of energy usage from high-

load periods to low-load periods, which can help reduce overall peak demand, and decrease the fossil intensity in the energy mix. While this approach may not currently be profitable due to the high costs involved, it could become a viable solution if battery costs decrease or if the costs associated with energy or installed capacity increase in the future.

As mentioned in section 2.1 ancillary services is used to stabilize the power system, and to ensure the supply. This enables opportunities to take advantage of the possibility to store energy in the BESS for DC-fast charging with external battery. This charging solution makes it possible to store surplus electricity in the external battery and to sell the electricity to the grid when the demand and price are high, as an ancillary service. Svenska kraftnät (2021a) provides a prognosis of the market for ancillary services will be equivalent to 2 350 M SEK/year in 2025, the reason for the increased cost is due to changes in the energy landscape. This is a market increase, compared to the year 2020 when the market corresponded to 1 055 M SEK/year (Svenska kraftnät 2021b). This could support the incentive for using the external battery for ancillary services and to obtain an additional source of revenue. As mentioned earlier, increased electricity prices have proved to be an incentive for BESS in terms of more effective energy usage and decreased yearly electricity costs. A scenario where this could be utilized at the same time as providing ancillary services could contribute to a potentially better business case with increased revenue. Which can increase the profitability of the investment. Potentially, this case could be used for the batteries used in a battery swapping station in a similar way.

6.5 Exploring Scalability

Aspects affecting the un-quantifiable criterion, *scalability*, are presented in Table 5.2. The presented aspects are not considered as strengths or weaknesses as the aspects can affect either way. In Table, 5.2 it can be noticed that grid limitations are affecting the possibility of up-scaling the DC-fast charging technology, which is further discussed in section 6.4. As the criterion *scalability*, refers to the possibility of up-scaling a charging station to supply a bigger demand or vehicle fleet, battery swapping is not similarly affected by the identified aspects. Battery swapping overcomes both geographical limitations and grid capacity limitations. However, it is affected by aspects of compatibility for up-scaling the charging solution. Referring to compatibility between components of the battery swapping station, the batteries used in the swapping process, and for external vehicles to be compatible with the station.

6.5.1 Grid limitations when scaling up HDEV charging

Charging time is an important factor since the time required to recharge electric vehicles impacts the total travel time (Abid et al. 2022). Connecting the identified requirements of short charging time and high power demand, significant challenges with power supply can occur, as discussed in section 2.1. In addition, logistic transports require high power charging on-shift (Borlaug et al. 2022). This limits the flexibility of when the power is needed and increases the risk of potential high power charging during high load periods in the energy system. In Sweden's energy landscape, there is a growing demand for high-power charging, yet the system is very limited by capacity and power. To address this need and balance the power demand, two potential solutions are external battery storage and battery swapping technologies. While both options offer benefits, battery swapping stands out as the fastest recharging solution compared to cable charging. This technology does not necessarily require high-power charging, as batteries are swapped during the recharging time instead of being charged.

DC-fast charging with external battery and battery swapping are identified as potential strategies for load management and handling the issue of limited capacity in the power system. Both systems are similar in energy use and the possibility to increase flexibility, however, Battery swapping additionally provides a charging solution that can be conducted in a few minutes, as seen in Table 4.5. According to Interviewee II (2023) DC-fast charging can be considered an emergency solution in comparison to battery swapping, which is an integrated system providing flexibility, reduced grid impact, and a substantially reduced charging time.

In the result presented in section 5.4.2 a scenario with decreased battery cost is presented. Where it is noticed that the investment cost decreases by approximately 3 MSEK, compared to the investment cost in the original case. Accordingly, the ROI results in 9.3 % and 13.5 % for utilization rates 30 % and 60 % respectively, as presented in Table 5.7. Compared with the original case, presented in Table 4.14, where

the ROI is expected to be 4.6 % and 6.7 % for utilization rate 30 % and 60 %. Similarly, the scenario for increased electricity costs is presented in Table 5.7 where the ROI is 14.5 % and 24.9 %. When combining the increased electricity costs and decreased battery costs, an even more profitable business case is obtained. Based on this the investment cost and the preconditions in the energy landscape affect significantly whether the solution is profitable and scalable or not.

6.5.2 Standardization for HDEV charging

There are several arguments supporting the need for standards to achieve a large-scale charging system for HDEVs in Sweden. Where the standards can help to fulfill an optimized, agnostic charging system that works for different vehicle fleets. Furthermore, a unified force of operators and OEMs deploying charging stations that are agnostic and can operate for different vehicle fleets. Although, it can be noticed that standardization is considered easier to implement for the technologies at a charging station, and more difficult for the vehicle hardware. As Interviewee II (2023) argued, battery swapping stations are considered easy to up-scale. A noticed obstacle in the scaling process involves standardizations for the batteries used for swapping. The argument is strengthened by the need for both size and dimensions for the batteries to match. Mao et al. (2023) argues that size and capacity are two of the main concerns for battery swapping in the distant future. The standardizations are especially important to achieve joint manufacturing throughout different OEMs. Where the batteries must be compatible with both the stations and the vehicles. Introducing policies can be seen as one important step toward a standardized battery swapping system, to adopt the charging technology on a larger scale.

Mao et al. (ibid.) argues that the acceleration of EVs in China is mainly driven by policies. For instance, the city of Chengdu introduced zero-emission areas in 2021 and restricted the traffic to be excluded from diesel HDVs (ibid.). There are several similar policies that accelerate the adoption of HDEVs in China, where the requirements and regulations are a driver. Furthermore, affecting the adoption also the subsidies given to manufacturers and OEMs. In 2017 the largest amount so far, of subsidies were given to OEMs of buses, trucks, and tractors, by the Chinese government (ibid.). Moreover, as mentioned earlier, China was an early adopter of the battery swapping process for charging vehicles. Where various policies are introduced supporting battery swapping in China (Ibold et al. 2022). Mao et al. (2023) presents a summary of existing policies affecting the battery swapping market in China, covering the years 2010-2022. Where it is noticed that the objectives of the policies accelerate the adoption of battery swapping, for example when defining targets on the number of swapping stations, and promoting the battery swapping concept. Whereas, in Sweden, there are no policies directly targeted to battery swapping, as noted in the mapping in section 4.7. Although, financial support is given to electrification projects, as mentioned in section 4.7 could possibly be given to battery swapping-related projects. Even if this would be possible, it requires actors and manufacturers to take action.

As mentioned earlier in section 4.6, there are different types of business models used for the battery swapping service. One advantage related to the technology is for the battery to be excluded from the vehicle, which could result in a cheaper investment cost for the vehicle. Although, this is something that is not covered in this study. But for the batteries to be outsourced from the vehicle owner, they could potentially be owned by either the battery swapping station operator or a third party. There are several other arguments for separating the battery and the vehicle, where the vehicle owners do not need to concern about the depreciation of the batteries, the battery range, and the battery waste management (Ibold et al. 2022). Ibold et al. (ibid.) emphasizes that due to the upscaling of battery swapping in China, there are partnerships emerging between battery service companies, energy companies, transport companies, and manufacturers.

6.5.3 Spatial implications of charging infrastructure

As mentioned in 2.2.1 there is a rising demand for semi-public and public chargers. International Energy Agency (2023) emphasizes that public charging infrastructure is a prerequisite for HDEV adoption, specifically localized in urban areas. In the early adoption of deploying charging infrastructure, the focus lies on main roads where immense traffic operates. The aim of this is to enable accessible charging solutions for freight. A noteworthy obstacle is the need for physical space for the charging stations which Interviewee II (2023) emphasized in the conducted interview. Charging HDEV by cable requires the vehicle to be parked at the station for a longer time. Providing sufficient charging solutions demand big physical space, which includes spatial implications. Although, it can be argued that geographical

space does not limit the deployment of charging infrastructure in Sweden. Where there are countries of considerably smaller areas that are facing real difficulties regarding geographical space.

During the conducted workshop, a discussion about how geographical limitations are not considered an obstacle was brought up. The situation in Singapore was mentioned. Due to its limited land area, Singapore faces challenges when it comes to deploying charging infrastructure for HDEVs. For this reason, Singapore stands in front of larger challenges for geographical space than Sweden. To overcome these hindrances, alternative solutions are considered. In Singapore, alternative strategies are adopted for deploying charging infrastructure. Alternative solutions and new thinking is stimulated when facing difficulties. This can be applied to the Swedish context which means that the spatial limitations are not as significant a hindrance to deploying charging infrastructure. To take advantage of alternative possibilities, when the geographical space is limited.

Although there may be sufficient geographical space, conflicting interests can be seen as an obstacle. When the land owners are prioritizing operations that will enable job opportunities. Where for instance, retailers or shopping centers could possibly be competing with land use. Despite the charging stations not directly stimulating employment prospects, their development can be politically supported. Where charging infrastructure is a necessity for achieving an electrified transportation sector and decreasing emissions. Accordingly, political subsidies or programs can promote land use dedicated to charging stations in Sweden. Where policies can help prioritize spatial land for deploying charging infrastructure. On the contrary, battery swapping overcomes the difficulties of geographical limitations as the station does not require the HDEVs parked at the station for a longer time. In a potential future scenario for charging infrastructure in Sweden, well-adopted charging stations may resemble the fuel stations that currently are operating. In a fully electrified transportation sector, a possibility could be to convert conventional fuel stations to charging stations for electric vehicles. Utilizing their favorable locations in connection to the roads. However, the conversion process would require significant planning and business management to be feasible.

6.6 The role of technological lock-in

Technological lock-in refers to a situation where an actor chooses one path, in terms of technology or similar, where the market later changes which put the actor in a potential technological lock-in. Therefore, it is favorable for the technologies to be agnostic and flexible to adapt to changed circumstances. The aspect of *technological lock-in* can also be considered if the innovation of charging technologies is slow and the development is passive. This can be applied to the context of Sweden, where DC-charging is the most dominant charging technology at present. The consequence of the early adoption of cable charging could include implications for other charging technologies to be operated in a later stage. The result can imply a case of a potential technological lock-in. For instance, it can be difficult to adopt battery swapping as a charging solution and likewise for battery swapping operators to enter the Swedish market. In China, battery swapping was included in a national strategy with the aim to accelerate the battery swapping vehicles and stations, as mentioned in section 2.3.3. Bernard et al. (2022) emphasize that to introduce alternative charging technologies, such as battery swapping, the implementation is hindered by political and business obstacles. Similarly, if Sweden would adopt the battery swapping system there could be a need for influential policies and regulations to accelerate the adoption.

The current policies and regulations affecting the charging infrastructure development in Sweden are mainly financial, as shown in Table 4.16. The policies and regulations are defined with the aim to support and accelerate the development of an electrified transportation sector. International Energy Agency (2022) argues that to overcome suboptimal solutions for the charging infrastructure in Sweden, there is a need for well-coordinated management regarding the support provided by stakeholders. Accordingly, an increase in political support could accelerate the development of charging infrastructure.

The investigated policies in this study are mainly focused on the electrification of the transportation sector in general, whereas some mainly focus on the charging infrastructure. Noticed is the minority of policies and regulations aiming specifically for heavy-duty freight. In the mapping presented in section 4.7, Global Drive to Zero is the one policy that focuses strictly on HDEVs. Most policies are targeting passenger EVs. Although, the market for passenger vehicles is more mature. Global EV Outlook of 2023 by International Energy Agency (2023) highlights that there is an upsurge of policies targeting the

HDEVs, which will be promising in terms of accelerating the deployment of charging infrastructure for trucks. Furthermore, to accelerate the deployment of charging infrastructure in Sweden, collaboration between the public and private sectors is necessary. This can involve funds and financial support provided by the government and for private actors to utilize these assets. To operate and implement the charging systems.

As presented in Table 5.2, standards are considered an important aspect of the three charging technologies. Standards can act as both an accelerator and a hinder to the deployment of charging infrastructure in Sweden. To achieve a unified charging infrastructure there is a need for standardization. International Energy Agency (2023) argues that costs, inefficiency, and other challenges for HDEV operators can be avoided when achieving interoperability and harmonious use of charging standards. Furthermore, the deployment of charging infrastructure will be affected by the development of standards. As explained in section 2.4, there are three main categories for standards regarding charging infrastructure. Where the categories are; the charging components, safety measures, and grid integration standards. Interviewee I (2023) argues that standardization for the sockets and ports needs to be assured. A focus of this study has been the charging components of the standards, which are considered important standards in terms of achieving interoperability and a well-functioned infrastructure. Although many of the components are covered by standards, the regulations for the standards implemented vary between countries (Das et al. 2020). Das et al. (ibid.) propose that every aspect of charging infrastructure for EVs must be standardized to uniformly operate electrical freight worldwide. To attain consistency, manufacturers of HDEVs and charging equipment need to collaborate in establishing universal standards. From another perspective, designing and implementing standards can be a time-consuming process. Manufacturers and charging technology providers need to act before the standards are implemented. Although, the result could imply a technological lock-in effect where standards are implemented later on. However, it could be argued that the market is in need of forerunners to accelerate its development. Unsure conditions could intimidate actors, but the ones who adopt early could gain positive effects in the long term. Accordingly, the market of charging infrastructure will gain support for the development if there are actors who are willing to lead, even though undeveloped standards and unsure market conditions.

6.7 Methodology discussion

This chapter will include a methodology discussion, where parameters such as the data collection, the variation of available data, the origin of the sources, and others will be discussed. The following sections will take validation, reliability, and generalizability into consideration.

6.7.1 Validation methodology

Validation refers to the validity and relevance of the methodology (Larsen 2017). This is applicable to this thesis in terms of the decision of criteria for the study. The investigated criteria are chosen to be investment, charging time, yearly electricity cost, climate impact, scalability, and technological lock-in. The six criteria are chosen to cover the aspects of technical, environmental, and economic perspectives. Although, the decision was made based on scientific literature and in discussions with the case company, the result could vary dependent on the decision of the criteria. The inclusion of more criteria, or a replacement of one or several of the criteria, would affect the outcome of the study. However, the decision of including six criteria in the study is supported by the fact that the evaluation is considering all defined perspectives. To ensure the general validity of the study, the university supervisor and the case company supervisors were overseeing the work throughout the execution of the thesis.

Multi-criteria analysis as a method has several advantages compared to informal judgments. Multi-criteria analysis is a flexible approach, the objectives and criteria for the analysis can practically be changed if necessary (Communities et al. 2009). In addition, the structured analysis will support the discussions and the decision taken and make it easy to follow the operations. An obstacle with decision-making, in general, can be when there are conflicting interests, this can often result in different recommendations (Doumpos et al. 2014). MCA overcomes this problem as one characteristic of the analysis is a multi-objective optimization, thus the analysis takes different factors into mind (ibid.). The result of the MCA will be considered as an indication of what will be interesting for future investigation.

To ensure the validation of the studied scientific literature, the chosen articles are published in academic

journals. One requirement for articles published in academic journals is for them to be "peer-reviewed", which means that the article has been critically reviewed to ensure academic relevance (Oliver 2012). This will ensure the credibility of the theory that illustrates the base of the study. As electric heavy-duty vehicles and charging infrastructure are developing technologies, there are up-to-date studies and investigations done in the field. At the same time, organizations currently working on strategies for the electrification of the transportation sector as an important part. This contributes to a big amount of reports that include comprehensive reviews of the technologies and policies. Therefore, this study includes reports as references to complement the scientific articles and to provide a current state of the development.

China and other Asian countries are forerunners when referring to electrifying heavy freight. This results in many of the used articles in the study having their origin in Asia. This may affect the study in terms of not being applicable to the Swedish context. A notable contribution is when presenting the investment cost for the battery swapping solution in Table 4.2, where the cost considers an Asian supplier that is not active in the Swedish market. The result is that the cost can not be exactly translated to the cost of a battery swapping station in Sweden. This could in fact affect the validation of the study, where the prices may not represent the costs in Sweden.

6.7.2 Reliability

Reliability is referring to the credibility of the study (Larsen 2017). Larsen (ibid.) describes the concept of reliability as if it is coherence between the data concerning the same information but from different sources, and high reliability is achieved when there are few measurement errors. To enhance the reliability of the data for this thesis, the approach for some of the data is to collect data from different sources and for these to be compared. However, this is not true for all of the costs as there was a limited amount of sources presenting costs.

A factor that can affect the reliability of the study is the decision of the components and their properties. Furthermore, the quantifiable criteria are determined by data from different sources. The data collection was conducted parallel for each criterion but the amount of available data varies. This could potentially affect the result in terms of reliability when a criterion only is built upon a limited amount of data. Detailed information about some of the components for the investigation is exclusively accessed from suppliers, which can make the reliability of the accessed data unsure, if reflected in the broader context. For the supplier of charging components for DC-charging the chosen actor is Kempower. To exclusively have one supplier where the data is collected can be a factor that will affect the reliability of the results. Regarding the data for the technical components of the charging technologies, it can be hard to access data about prices and costs. Therefore, the information collected is compared with information from different scientific articles but also internal information from the case company.

The data for traffic distribution is collected in 2019, which may not be reflective of the current traffic distribution. Furthermore, the data for traffic distribution was limited and could potentially affect the assumption that the demand for the charging stations is considered the same as the traffic distribution. The investment cost has varying reliability where some of the presented cost posts correspond to the actual price given by suppliers of the components, whereas other refers to assumptions made on a theoretical base. Particularly, the investment cost from a theoretical base concern the robotic arm, and the battery swapping station.

Furthermore, when conducting the calculations needed for DC-fast charging with external battery in section 2.3.2, assumptions are required. Noteworthy, the assumption of the charging efficiency for the external battery is 100%. The VRFB battery chosen for the study is proven to include high efficiency, as mentioned in section 3.2. However, there are limitations to the transmitting power, and to increase the reliability of the study a lowered charging efficiency would be applied.

When assessing the criterion climate impact from electricity use, as presented in section 4.5, assumptions are needed and defined to conduct the calculations. Considering the unpredictable development of the energy landscape, the assumptions can be affecting the reliability of the study. Chosen for the calculations is what energy sources are on the marginal for the periods of interest, where wind power and coal condensing power plants marginal sources are considered in this study. Furthermore, the calculations are dependent on the subdivision of high-cost hours and low-cost hours, as presented accordingly in

section 4.5. Potentially the calculations could be further profound, and other assumptions could be implemented. Different time periods or the energy sources on the marginal could be defined, which would affect the outcome of the assessment. Furthermore, it is difficult to predict the efficiency rate of the coal-fired power plant in a future scenario. Which correspondingly is an assumption to consider. The marginal approach for calculating the electricity cost is chosen rather than the residual mix approach, which similarly could result in a different outcome. The decision was based on the fact that the marginal approach is better suited for investigating changes in electricity use, which is the case for this study, as explained in section 2.1. Furthermore, the climate impact is delimited from including solely the climate impact from electricity generation. Notably is, that there are additional impacts from other factors such as the battery construction or various utilization rates of the charging stations. However, this has been delimited to be included in this study but is of interest in future studies as this can affect the decision of deploying charging infrastructure in the future.

6.7.3 Generalizability

The context of generalizability refers to the extent to which the results can be used in other contexts (Larsen 2017). The method is chosen to rely on three specific vehicle fleets and more specifically two types of vehicles, that are autonomous HDEV and HDEV. This makes the result applicable in other circumstances where HDEVs are included.

The study relies on the circumstances of Sweden. This makes the result not generalized for all locations. For instance, referring to the electrical spot prices which have a significant impact on the output. The case study involves the prices for the Swedish electricity bidding area SE3, which can make generalization in a Swedish context complicated as well. For a more generalized study, a sensitivity analysis including the different electricity bidding areas could be included. Although, this is not the case for this study as the prioritizing sensitivity analysis refers to future scenarios for the energy landscape and cost trends. Furthermore, the study is not applicable to a global context as yearly electricity costs refer to the Swedish cost structure.

However, the theoretical contribution from scalability and technological lock-in can be generalized in a broad context. The criteria are established considering a Swedish context, although some of the challenges and drivers can be similar in an international context and therefore increase the generalizability of the study.

7 Conclusion

Investment, charging time, yearly electricity cost, climate impact, scalability, and technological lock-in, are determined criteria that will be considered in the study. These criteria directly affect the decision of strategy for deploying charging infrastructure. The chosen criteria provide economic, technical, and environmental considerations and are relevant for the development of charging infrastructure, which answers *research question 1*.

When assessing the charging technologies from the six criteria following conclusions can be drawn.

DC-fast charging has a relatively low investment cost, however, there are other challenges that DC-fast charging encounters. Yearly electricity cost is high since the technology lack capacity to manage the load. For the same reason, DC-fast charging also has a significant part of the electricity use during periods when coal-condensing power plants are on the margin in energy generation. If a scenario with increased electricity cost would occur the energy costs could increase substantially. However, DC-fast charging can be considered mature and aligned with the current policies in Sweden.

DC-fast charging with external battery involves high investment costs which is an implication of the immense cost of the BESS. Although, if the estimate of decreased battery costs becomes a reality the case would be more competitive and is proven to result in a decreased pay-back time when compared to the original case. The BESS enables load management, which marks the possibility to manage electricity use. Hence, the beneficial results for the criteria of yearly electricity cost and climate impact. This since the external battery is able to overcome the limitations related to capacity in the power grid. Furthermore, a scenario in which the electricity cost increases the flexible use contributes to the charging technology to be proven more competitive.

Battery swapping is characterized by a very short time frame for recharge of the vehicle. In addition, battery swapping has the capacity to manage the load which implies possibilities to reduce the energy costs and the emissions from electricity use. On the other hand, battery swapping is not adopted for HDEV in a European context. Battery swapping also requires extensive collaboration between various actors and a transformation of the business model for vehicles and charging. Lastly, the adoption of battery swapping requires a shift in charging infrastructural design and strategies in Swedens, including policy making. This is because battery swapping is dependent on compatibility between vehicles, swapping stations, and batteries.

Policies and standards are influential for all charging technologies. Regulations can contribute to an acceleration of the deployment, where policymakers can address actions to be influential for the charging infrastructure development. This summarizes how the charging technologies perform against the defined factors, hence *research question 2*.

When comparing the charging technologies based on the criteria it can be noted that all solutions face extensive challenges connected to insufficient grid capacity. However, DC-fast charging with external battery and battery swapping have the capability to handle the challenges in contrast to DC-fast charging. This implies that the two charging technologies comprise reduced climate impact in comparison to DC-fast charging. Even if both DC-fast charging with external battery and battery swapping are characterized by load management possibilities, DC-fast charging with external battery can be considered easier to deploy than battery swapping, in the current Swedish context. This since battery swapping is not adopted in the European context yet, where business models and standards for battery swapping are currently lacking. However, battery swapping has significant advantages in overcoming challenges in similarity to DC-fast charging with external battery. Simultaneously battery swapping offers other advantages compared to DC-fast charging with external batteries, including shorter charging times and the ability to overcome geographical space limitations. When it comes to investment, DC-fast charging has lower costs and is more aligned with the current state of policies in Sweden than the other two. This answers the advantages and limitations of the charging technologies, in line with *research question 3*.

7.1 Further work

As this study has been conducted over 20 weeks by two authors, the resource of time has been a limiting factor. There are areas that the authors believe would diversify the result further and contribute to the research field.

In the context of energy costs and the energy system, it would be interesting to include a more extensive study around ancillary services, including calculations on the profitability of using the external battery in the case study. This could potentially strengthen the business case for external battery which also would be a strategy to tackle the challenges around limited grid capacity. Additionally, it would be of interest to have a sensitivity analysis, a sensitivity analysis around a scenario where the electricity costs decrease, to investigate the profitability of external batteries. In contrast to the scenario in section 5.4.1 where the electricity costs increase.

Furthermore, in the criterion climate impact, the impact from the utilization rate of 30% is of interest to see how the increased utilization affects the climate impact. In this criterion, a sensitivity analysis using different marginal sources and time periods could diversify the result.

Battery swapping is a technology that was limited in the quantifiable criteria, due to the difficulties with finding data applicable to the Swedish context. This concerns the criteria investment cost, yearly electricity cost, and climate impact. Diversifying these criteria with applicable data would increase and strengthen the comparison between the technologies.

Finally, there could be other criteria that are important to cover when assessing charging technologies, there is also a large number of other technologies and solutions that could be included in the assessment as well, in order to create a broader perspective.

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Appendices

A Appendix - Semi-structured interviews

A.1 Interview questions

The interviews aim to attain knowledge from researchers within the field of electrified transportation and charging technologies. Questions below are used for the semi-structural approach, where the question may differ in formulation and order during the occasion of the interviews.

1. Describe your background within electrified transportation.
2. What identified obstacles and opportunities are there when aiming to electrify the Swedish transportation sector?
3. Charging efficiency
 - Is it possible to base the logistics system of the future on a downtime of approximately 2 hours, which is the normal charging time for heavy electric trucks? This is in contrast to the relatively short refueling time of conventional diesel trucks.
4. Grid impact
 - An aspect of electrification is its impact on the power grid. How can charging times be made flexible to facilitate its impact on the grid?
5. Scalability
 - Will battery swapping work on a large scale?
6. Technological lock-in
 - What identified risks are there when there is no standardization for charging infrastructure?
 - How likely is it that standards for charging infrastructure will be introduced in Sweden?
 - Is standards a prerequisite for development?
 - How should a company in the market act when designing vehicles and charging infrastructure before there are standards for development?
 - Should they go for a broad approach or choose one technology?
 - What are your views on battery swapping and cable charging for logistics vehicles in logistics systems?
 - Is it possible for both cable charging and battery swapping to be part of the solution?
 - How should vehicle manufacturers and charging infrastructure providers act to select technologies without being technically locked in?

B Appendix - Workshop

B.1 Discussion questions

The workshop was conducted to share the result for the case company and get different perspectives and feedback on the work. The questions presented below served as the fundamental framework for the deliberations held during the workshop. Prior to each discussion section, an introduction to the thesis findings of the area was presented.

1. Scalability

- Is geographical space a hinder for large scale electrification? How can geographical space limitations be overcome?
- What role does grid capacity play in determining the scalability of charging solutions? Does the government need to address actions for grid expansion at a larger scale?
- Are standards a prerequisite for up-scaling?

2. Technological lock-in

- What policies are needed to accelerate the development of charging infrastructure?
- Is the influence from the government sufficient for a company providing charging infrastructure to accelerate electrification?
- Is collaboration between actors a prerequisite for large scale electrification?
- What are the risks of solely adopting one charging technology?
- How do varying international charging standards impact global transportation?

3. Battery swapping

- What is needed for implementing battery swapping in Sweden?
- What advantages do you see with the features of battery swapping?