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Increasing the use of battery electric trucks in line-haul operations

An analysis of the enablers and barriers for electrification in the transportation system - from a network perspective

Master's thesis in Supply Chain Management

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Cover: The heavy duty Battery Electric Truck used in the E-Charge project (Lindholmen Science Park, n.d.)

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Abstract

There is increasing pressure to decarbonize the transportation sector as a response to the climate change, the climate targets, and the European Union´s target of reaching net-zero emission by 2050. This Thesis investigates the introduction of electric trucks (BETs), into DB Schenker´s line-haul operation, with focus on the technical, operational, and economical feasibility. A mixed-method approach was used, including a multiple case study, where three routes from DB Schenker´s transportation network were analyzed, focusing on total cost of ownership (TCO), and supported by interviews with key stakeholders involved in the transformation to electricity on these routes. The Thesis also uses the ARA-framework to analyze how actors, resources and activities influence and enable this transformation. The findings show that while introduction of BETs offer both environmental and cost benefits in the long run, the transition faces challenges in terms of infrastructure development and cooperation between actors in the transportation ecosystem.

Keywords: Battery Electric Truck, Line-Haul, DB Schenker, Electrification

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Our warm thanks also go to Andreas Andersson, our supervisor at DB Schenker Consulting, for his unwavering support, practical insights, and for helping us gain access to internal meetings and resources that enriched the empirical part of our work. His engagement ensured that our research remained aligned with the company's expectations and real-world relevance.

Finally, we would like to thank all the professionals who took the time to participate in our interviews. Their openness and reflections provided us with invaluable perspectives on the ongoing transformation of the transportation system, and helped us better understand the complexity of transitioning to battery electric trucks.

Thank you all.

Gustav Andersson & Jesper Nordgren, Gothenburg, June 2025

List of abbreviations

Abbreviation	**Meaning**
BET	Battery Electric Truck.
BM	Business Model.
BESS	Battery Energy Storage System.
CI	Charging Infrastructure.
CLD	Carbon Loading Density.
CO_2e	Carbon dioxide equivalent.
CPO	Charge Point Operator.
DN	Distribution Network.
EU	European Union.
FCEV	Fuel Cell Electric Vehicle.
GHG	Greenhouse Gas.
HCT	High-capacity transport.
HVO	Hydrotreated Vegetable Oil.
ICET	Internal combustion Engine Truck.
OEM	Original Equipment Manufacturer.
TCO	Total Cost of Ownership.
TN	Transportation Network.
V2G	Vehicle-to-grid.

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1

Introduction

The following chapter outlines the background of the thesis, followed by DB Schenker Nordics perspective and aim. The background highlights current climate objectives and introduces electrified road transportation as a solution to mitigate the negative development. The DB Schenker Nordics perspective presents the company's climate objectives and their overarching strategy to achieve these, emphasizing electrified road transport. Lastly, the aim defines the purpose of the thesis, focusing on the introduction of Battery Electric Trucks (BETs) in DB Schenker Nordics' line-haul operations.

1.1 Background

During the past decades, the climate has seen a negative development with global temperatures and extreme weather, because of increased greenhouse gas (GHG) emissions (Abbass et al., 2022). This has put pressure on a transition to environmentally neutral alternatives to mitigate and subsequently reverses this trend. By 2050, the European Union (EU) is devoted to achieving net-zero GHG emissions, which also aligns with the Paris Agreement target to limit global warming to 1.5-2°C above pre-industrial levels (European Commission, 2019). The second-largest sector of carbon dioxide emissions is the transport sector, responsible for 21 % of the world´s total (Tiseo,2025). Furthermore, road transportation accounted for 73% of all emissions in the transportation sector in 2022, evidently making road transportation one of the largest contributors to GHG emissions (European Environment Agency, 2023), with trucks and buses accounting for 35% of the road transportation emissions, even though they only account for 8% of all four-wheeled vehicles on the road. (International Energy Agency, 2024).

To decrease the negative climate impact of road transportation, substituting the transportation fleet with electric trucks is a viable alternative, and the technology of electric trucks has one of the lowest life-cycle impacts when different technologies are compared (Gillström, 2024). Furthermore, a transition towards electrical trucks brings requirements in terms of enhanced electrical grid charging infrastructure and batteries capable of powering heavier trucks for an extended range (International Energy Agency, 2024).

DB Schenker is a global company providing services within logistics and supply chains, such as air, ocean, and road transportation solutions. The company's environmental and climate focus is clear with a vision to achieve sustainable growth. One of their main objectives is to become climate neutral by 2040, with a sub-objective of reaching a 25% decrease in Carbon dioxide equivalents (CO_2e) before 2030. To achieve this, their focus is on reducing the overall environmental impact of their products and operations by shifting away from diesel, towards renewable energy alternatives such as electricity and hydrogen. The total emissions from DB Schenker's business were 17.9 million tons CO_2e in 2022, where land transportation (truck operations) accounted for 3.3 million tons CO_2e (18%), which illustrates great opportunities to improve the environmental impact by switching to and incorporating an electric transportation fleet on land.

In light of this, this master's thesis will analyze the possibilities and barriers associated with electrifying DB Schenker's transportation fleet, including external haulers, with the narrowed focus on three routes which will act as a general representation of their transportation network. The structure of the report is as follows: the remaining part of chapter 1 presents DB Schenker Nordics Perspective in the light of their transformation journey into green transportation, followed by the aim of this thesis. chapter 2 presents previous research related to the electrification of the transportation system and heavy-duty trucks. Chapter 3 describes the problem and the specific research questions that this master's thesis aims to answer. Chapter 4 presents the methodology that is used for this project, and chapter 5 introduces the theoretical framework that is used to analyze the results. Chapter 6 outlines the foundation for the calculations for the case study, and Chapter 7 presents the result from these cases. Chapter 8 outlines the empirical findings of the business network study, followed by chapter 9 which presents the analysis for this thesis, for both the cases and the business network study. Finally, chapter 10 presents the discussion and chapter 11 the conclusion for this master's thesis.

1.2 DB Schenker Nordics Perspective

This report will focus on DB Schenker Nordics, which consists of DB Schenker's businesses in the Nordic countries, and not DB Schenker as a whole. The DB Schenker Nordic cluster consists of multiple companies, namely, Schenker Oy, Schenker A/S, Schenker AS, Schenker AB, Schenker Logistics AB, Schenker Åkeri AB, Schenker Consulting AB, and Schenker Property Sweden AB. Schenker Åkeri AB is the subsidiary hauler company of DB Schenker Nordics and it handles roughly 25% of DB Schenker's transportation assignments, with the other 75% being handled "externally" by multiple different and smaller hauler companies. This company structure is illustrated in Figure 1.1. DB Schenker Nordics offer a wide range of products and services, such as contract logistics, industry solutions, as well as air, ocean and land (road) transportation (DB Schenker, 2023).

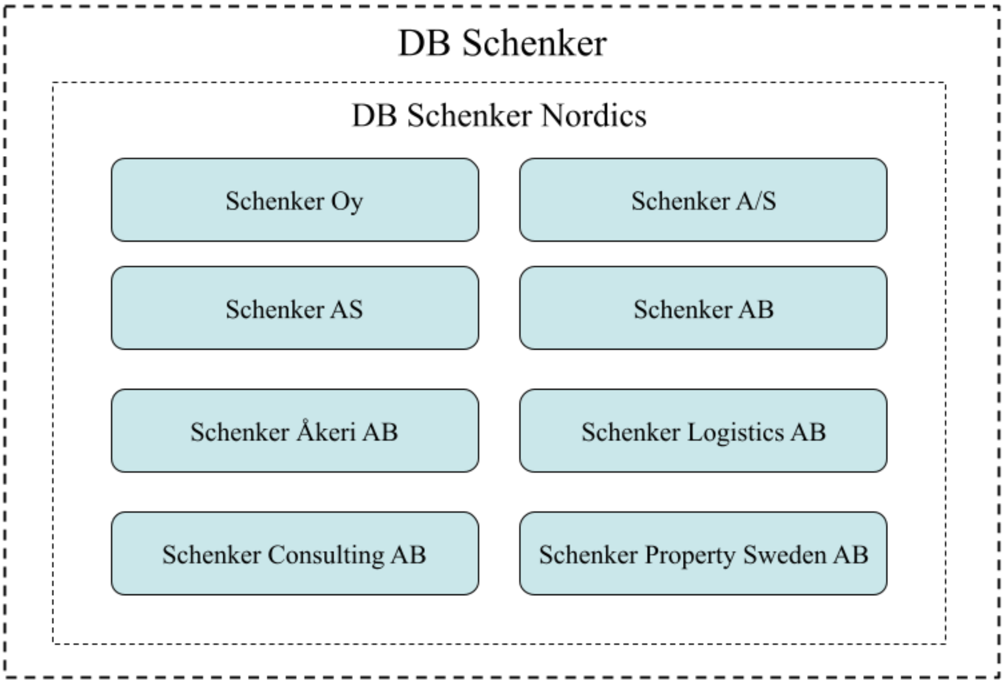


Figure 1.1: An illustration of DB Schenker's company structure.

DB Schenker's sustainability strategy is organized into three strategic dimensions; Clean Logistics, Thriving Workplace, and Trusted Supply chain (DB Schenker, 2023). These dimensions each reflect different aspects of the UN's Sustainable Development Goals, which are explained in Figure 1.2 below.

Clean Logistics

13. Climate action
- We reduce our dependence on fossil fuels
- We transition to zero-emission technologies
- We increase awareness of and commitment to decarbonization

7. Affordable and clean energy
- We buy hydro, solar and wind electricity
- We continuously increase our number of solar panels
- We systematically reduce our energy needs

11. Sustainable cities and communities
- We develop new transport solutions for urban environments
- We transport goods using electric vehicles
- We shift to renewable fuels

12. Responsible consumption and production
- We increase our share of renewable fuels
- We choose products made from renewable or recycled materials
- We recycle the resources we have used
- We minimize our use of chemical products

Thriving Workplace

3. Good health and wellbeing
- We work systematically to ensure a healthy workplace
- We implement a number of wellness initiatives
- Our employees receive a wellness allowance

5. Gender equality
- Our steering group for equal treatment runs our equal treatment program
- We conduct regular salary surveys
- We train our staff in equality

8. Decent work and economic growth
- We have good union collaborations
- We have zero tolerance for harassment
- We have a supportive environment for parents
- We work closely with our partner hauliers

10. Reduced inequalities
- Our steering group for equal treatment runs our equal treatment program
- We play the LIKA game – our game to provoke discussion about prejudice and discrimination

Trusted Supply Chain

9. Industry, innovation and infrastructure
- We pursue innovation projects to find new sustainable solutions
- We improve our infrastructure to support sustainable operations

4. Quality education
- We provide training for our own and our partner hauliers' employees
- We provide training for our managers

17. Partnerships for the goals
- We collaborate with customers, suppliers and other key stakeholders
- We meet with authorities and other decision-makers to discuss the effects of different policies

Figure 1.2: The sustainability strategy of DB Schenker Nordics (DB Schenker, 2023).

As previously mentioned, DB Schenker (2023) has set an ambitious sustainability goal of becoming climate neutral (covering Scope 1–3 emissions) by 2040 and having targets to reduce 25 % of absolute CO_2e emissions by 2030 (Scope 3 -25% and Scope 1 & 2 -42%, based on a baseline from 2021). By 2040 they plan to exit from diesel, kerosene and marine fossil fuel and switch to electricity and hydrogen. These goals are complemented by initiatives to transition to renewable energy sources and implement efficiency improvements across the transportation chain.

DB Schenker Nordic is actively electrifying their fleet, mainly by introducing electric parcel vans for urban distribution. In Finland they have introduced the first fully electric high-capacity transportation (HCT) truck for regular operations. In Sweden, DB Schenker is involved in the E-Charge (Lindholmen Science Park, n.d.) project, testing BETs for long-haul applications together with multiple actors, such as Chalmers, ABB, and Scania. The aim of these initiatives is to pave the way for a broader transition to low-carbon vehicles, although they identify that full electrification of heavy-duty road transportation is a complex task.

DB Schenker Nordic is also investing in other renewable fuels like HVO and biogas, as a transitional solution to lower their emissions in cases where BETs are not yet commercially viable. Furthermore, DB Schenker Nordic also recognizes that adjustments to their infrastructure and operations are necessary to facilitate their long-term strategy, such as installing charging infrastructure and re-evaluating terminal designs accordingly. They also want to ensure that their move towards electricity as a fuel source can support their future increased demand without compromising on transportation efficiency or quality. DB Schenker Nordic identifies that collaboration with other actors in the transportation system is central and important to reach their sustainability goals. Working closely with other actors such as truck producers, haulers, and charge point operators (CPOs) and sharing and developing knowledge to create solutions that can overcome barriers related to the electrification of heavy-duty trucks. This cooperative approach is also believed to help align the operational practices with future new sustainability targets, and in navigating the challenges related to future regulations and market conditions.

1.3 Aim

The aim of this master's thesis is to analyze possibilities and barriers associated with electrifying DB Schenker's transportation fleet. More specifically this report will focus on the possible introduction of BETs in DB Schenker Nordics' line-haul operations, through a case study of three different routes in their transportation network. Additionally, the report seeks to analyze the interconnected business network, consisting of actors, resources, and activities, and how this network influences the introduction of BETs in DB Schenker's operations. The aim and purpose of this report is further discussed in chapter 3.

2

Previous research

This chapter outlines the previous research relevant to this thesis and is divided into two sections. The first section covers previous research regarding the system and network perspective of battery electric trucks, followed by a section focusing on previous research on the technical aspects of battery electric trucks.

2.1 System and network perspective of electrification of trucks

This section outlines a holistic perspective of electrification of trucks and the importance of understanding this broader perspective. Starting with an introduction to the transportation system in this section. The following subsections delve into the dynamics of the transportation system, how understanding of the system creates opportunities for new business models when electrifying freight transport, and finally the barriers and enablers of electrification.

The transportation system can be described as a complex open system that consists of three main layers or sub-systems: the supply chain layer, the transportation layer, and the infrastructure layer (Browne et al., 2022). The supply chain layer refers to the material flow of production, purchasing, and selling of products across the supply chain network. This layer can be described as a tightly coupled system with collaborative business relationships. The second layer, the transportation layer, consists of the actual transportation activities and the flow of transport. This layer is described as a loosely coupled system where actors are fragmented and independent. The final layer, the infrastructure layer, refers to the transportation infrastructure, consisting of resources such as roads, rails, or terminals. This layer is a tightly coupled system due to the large investment costs of infrastructure and the consequent lock-in effects.

Between these layers there are two interfacing markets that connect the different layers: the transportation market and the traffic market (Browne et al., 2022). The transportation market connects demand of material flow in the supply chain layer with the supply of transportation flow services of the transportation layer. This connecting market is generally dominated by loose couplings between the two layers. The other connecting market between the transportation layer and the infrastructure layer is the traffic market. This market serves as an interface between the resources of both layers, connecting, for example, the infrastructure's supply of roads with the transportation demand of road vehicles. There are loose couplings between the layers for road transportation, since road transportation is more flexible compared to rail, sea, and air transportation. A summary of the transportation system and its tight and loose couplings is illustrated below in Figure 2.1.

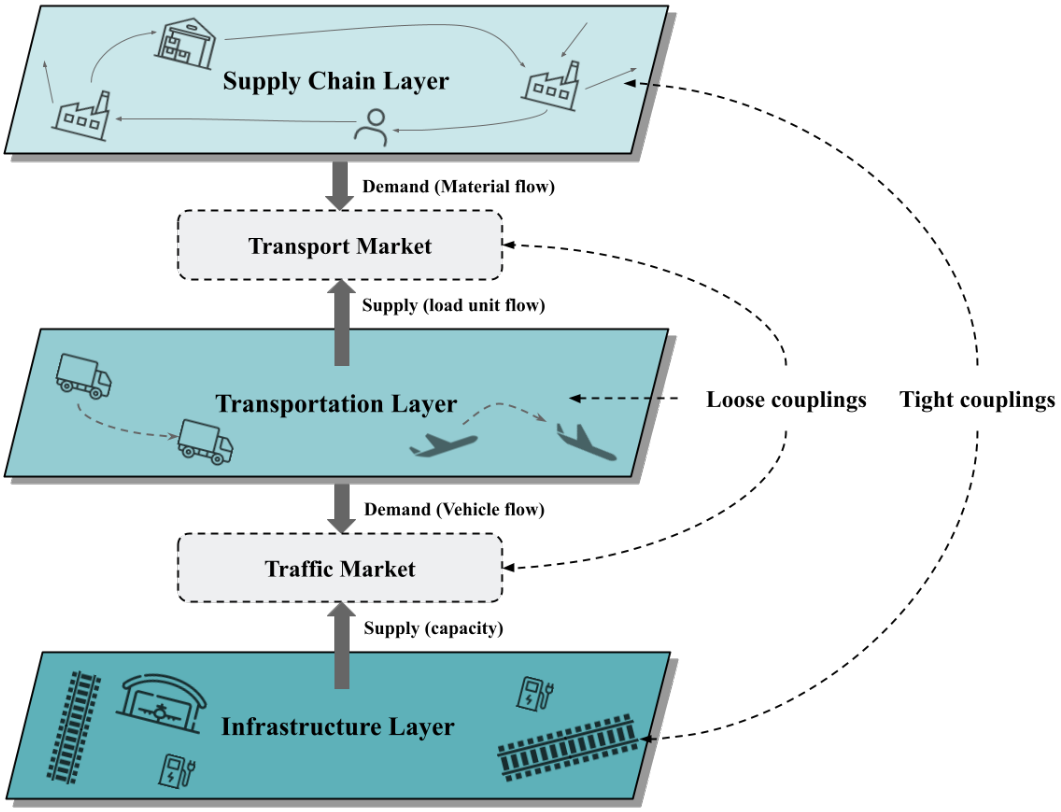


Figure 2.1: The transportation system and its couplings (based on Browne et al., 2022).

Browne et al. (2022) suggest that the entire freight transportation system is loosely coupled, as both the transportation layer and its connecting markets exhibit this characteristic. A loosely coupled system favors short-term efficiency and resists large-scale change, which could inhibit progress toward a more sustainable freight transportation system and making it difficult to electrify road transport. This is because the electrification of road transportation requires adjustments to the system, which challenges the current system and would change the couplings between the layers. The following subsections go into more detail of what this loosely coupled system entails for different actors in the system when electrifying trucks.

2.1.1 The system dynamics of the transportation system when electrifying trucks

Raoofi et al. (2024) highlights the system dynamics of the transportation system, previously described by Browne et al. (2022), when electrifying road freight transport. Raoofi et al. (2024) state that it is difficult to make strategic decisions regarding electrification of trucks, due to the high complexity of the system. There are also “chicken-and-egg” dynamics in the system making it difficult for actors to make changes. One such example is that BETs require charging infrastructure to operate, but actors have low incentives for building said infrastructure if there are not any trucks on the market to use their chargers. Having a system-level knowledge and understanding the system dynamic becomes important to understand how electrification impacts the road freight transportation system as a whole. Raoofi et al. (2024) argue that comparing total cost of ownership (TCO) between BETs and internal combustion engine trucks (ICETs) only reflects the perspective of a few select actors and not the system as a whole. Furthermore, changes in the system cannot be seen in isolation since multiple components are interconnected. Consequently, the solution for the complex and interconnected problem of road freight transportation electrification requires coordination between different actors, such as manufacturers, logistics providers, infrastructure providers, and policymakers.

Raoofi et al. (2024) classify the dynamic impacts of electrification into direct impacts, induced impacts and policy interventions, which are split into two categories of operational and structural variables. Direct impacts refer to a direct consequence of electrification, such as increased vehicle cost. Induced impacts are induced from a ripple effect of direct impacts, such as changes in routing of the vehicles due to charging requirements. Policy interventions refer to the impacts that policy changes might have on the system. The direct impacts will mainly impact the system in the transportation layer and traffic market, which then leads to and accumulate into induced impacts in the rest of the system. Meanwhile policy interventions will impact the system in the infrastructure layer and the traffic market.

These cause-and-effect relationships can be described and mapped in a causal loop diagram (CLD), where feedback loops of reinforcing and balancing nature are presented (Raoofi et al., 2024). An example of a reinforcing loop for electric trucks is the awareness-loop, where technology awareness rises as the market share of electric trucks increases, making the further adoption of electric trucks more attractive. In contrast a balancing loop is, for example, the access-to-charging-loop. When the electric truck market share increases the demand for charging also increases, which could create a market gap between the demand and the supply of charging infrastructure, resulting in electric trucks becoming less attractive.

The role of policymakers will be pivotal in moving the entire system towards sustainability, since changes in policy have knock-on effects in the entire system (Raoofi et al., 2024). Liimatainen et al. (2019) highlight that the transformation of BETs would be facilitated by policy interventions including allowing increased gross weight of the truck and thereby enabling a larger battery. This is also emphasized by Cheng & Lin (2024), describing that the government and policymakers play a crucial role in accelerating and facilitating the adoption of BETs, through effective policy measures and interventions, as well as providing support in the development of charging infrastructure and battery technology advancement, hence reducing prices and consequently barriers for fleet operators (Cheng & Lin, 2024). For policymakers to make informed decisions they also need to understand the dynamics of the system as a whole, to fully understand the impact of their decision making (Raoofi et al., 2024).

The interconnectedness of the variables in the system makes it difficult and complex to change (Raoofi et al., 2024). Consequently, there is no clear starting point for actors in the system when starting their electrification journey. Understanding the system dynamics and having a holistic view of the system thus becomes important for actors to be more proactive and quicker to react to induced impacts. Furthermore, having this holistic view can be beneficial for actors to identify and understand the importance of other actors in this complex system and how they could or should collaborate and form relationships with them when electrifying their operations.

2.1.2 Business models for electric trucks

According to Dehkordi et al. (2024), it is important for companies to have a system-level or an ecosystem perspective to design successful business models (BMs) when electrifying freight transport. Currently many logistics companies are struggling to integrate BETs due to challenges in the surrounding business ecosystem, such as grid capacity and charging infrastructure. But these challenges can also be seen as an opportunity for the companies to develop new BMs and capture "unrealized value". Business ecosystems describe how companies are dependent on other actors and resources, such as suppliers, customers, capital and infrastructure. Companies try to capture the value of these "inter-firm connections" through their BMs.

Dehkordi et al. (2024) explain the different "design themes" of business models, which are: novelty-centred, lock-in, complementarity-enabling, and efficiency-enabling BMs. A novelty-centred BM captures value by creating new ways of conducting business in the ecosystem. A lock-in BM utilizes interdependencies and relationships between different actors to disincentivize them from leaving the BM and switching to competitors, by incentivizing repeat transactions through high switching costs or positive network externalities. Complementarity- enabling BMs increases the value proposition by combining different products or services that complement each other and lead to an increased perceived value when combined with each other. Efficiency-enabling BMs aims to increase efficiency and reduce costs by minimizing waste or optimizing resource usage. These BM themes are not mutually exclusive and can instead coexist and engage with each other in a company's single BM.

The article examines different BM in the BET ecosystem and connects them to the corresponding BM themes. The study found that novelty is the most common theme among the studied BMs, since the BET ecosystem is still emerging and developing. Novelty can sometimes be seen as having a weak negative interaction with each other due to their different nature. This is not the case however in BET, since cost efficient BMs are what allow novel BMs to compete with the BMs of ICETs and to be adopted. The road transportation and logistics industry have low margins, which is why efficiency is crucial to remain profitable. Transitioning to BET thus requires careful planning and investments to increase the efficiency of the vehicle fleet, such as investments in fleet management systems and charging infrastructure. This relates to the domain of lock-in because adoption of a certain system or infrastructure requires a large investment and thus has a high switching cost. The interconnected ecosystem of actors in the BET area need to collaborate with each other to create and allow for adoption of novel BET BMs. The authors state that:

> *"The success of businesses in such ecosystems depends not only on their own activities but also on the activities of other companies and the relationships between them. By adopting an ecosystemic approach in BM design, companies can better understand the needs and preferences of various participants and recognize potential complementarities."*
>
> *"Complementarity enables firms to create value by combining their resources and capabilities with other ecosystem actors, leading to new and innovative BMs. Thus, complementarity has become a critical driver of BM design in the ECV [BET] ecosystem, as it facilitates cooperation, innovation, and value creation."*

This suggests that companies should apply an ecosystem perspective and identify the different roles of actors, the interdependencies in the system, and the opportunities for co-creation, to design successful BMs of novelty and complementarity. The co-creation requires relationships and partnerships with other actors in the ecosystem. Establishing relationships and partnerships can also help with the lock-in aspect of the BM.

2.1.3 Barriers and Enablers for electric trucks

Gillström (2024) identifies and describes barriers for the transition to electric freight transportation of logistics companies and how these can be managed. This transition involves multiple actors such as logistic companies, OEMs, transportation buyers, municipalities, and new actors to the transportation system such as charge point operators and energy companies. The transportation system is currently characterized by low margins and that transportation buyers are price sensitive, often buying at the lowest possible cost. The system is also time-sensitive, where logistics companies often have a 15-minute delivery window and that delays can lead to large costs. According to Gillström (2024) the transportation sector can also be described as "patriotic" where large changes are met with resistance, which is in line with the description of the system by Browne et al. (2022).

Gillström (2024) classifies four categories of barriers for the transition to electric freight transportation of logistics companies. Namely, practical & technological, financial, institutional, and cultural & social. Practical & technological barriers refer to aspects such as limited range of BETs, longer lead times due to charging or losing load capacity due to the weight of the battery. The impact of these types of barriers can vary depending on the context of the transport, where it is stated that urban distribution and line-hauls have lower barriers compared to long haul batch deliveries. Financial barriers relate to the high investment costs of BETs, costs stemming from decreased operational flexibility, and price of charging. Institutional barriers are barriers in the current layout of the transportation sector, such as lack of charging infrastructure. These types of barriers highlight the complexity of the system where different actors are impacted in different ways and take different risks. The high investment cost of BETs affects the haulers for risk, while the LSPs are concerned with the performance of their system. Meanwhile transportation buyers gain the benefit of fossil-free transportation from these risks. Cultural & social barriers refer to the “patriotic” and change resistance of the transportation sector, where LSPs and haulers are afraid to take on risk in their already low-margin business.

Gillström (2024) presents three different strategies for managing these barriers and what instead enables the transition to electric freight transport. The first strategy is to quantify uncertainties and loss of flexibility in terms of cost, such as translating an increase in lead times or late arrivals into actual costs, so that it becomes more transparent what costs the change will entail. The second strategy is to categorize the transportation system into different subsystems, in terms of open, closed, static or dynamic systems. Where line-haul deliveries can be described as a closed and static system, highlighted by higher predictability, fewer actors and easier to control. Urban deliveries can be seen as a closed subsystem while also being dynamic due to the large fluctuation in routes driven each day. Long haul batch deliveries are the most difficult to electrify and control, due to being both an open and dynamic system. The third strategy is to develop deeper collaborations among actors in the transportation system and move away from transactional relationships and instead towards partnerships. For example, by increasing contract length to support the necessary large investments in the BETs and in the infrastructure, sharing the issues and costs described as financial barriers.

2.2 Technical aspects of battery electric trucks

The following section outlines previous research and background to the more technical aspects of electrification of trucks, to explain important factors for the case study, which will be further described in chapter 3.

2.2.1 Total cost of ownership

According to Karlsson & Grauers, (2023) BETs are more cost-effective compared with diesel trucks when looking at a route equivalent to 550 km and when the carried weight is not considered significantly heavy. This advantage can partly be explained by the fact that BETs can charge during mandatory breaks, as well as line-haul trucks having high battery utilization. Battery utilization is also emphasized by Vijayagopal & Rousseau (2021), describing that battery utilization is a significant factor in reaching TCO parity between BETs and ICET. If BETs are not utilized in the way they are designed for, e.g., driving shorter routes with BETs that have batteries designed for long routes, will consequently reduce potential energy savings and make BETs less competitive from an economic perspective (Vijayagopal & Rousseau, 2021). However, Karlsson & Grauers, (2023) describe that the driving pattern is also a factor heavily affecting cost effectiveness, and Burnham et al. (2021) highlight the labor rates as a critical factor when charging BETs. On occasions where charging is significantly time-consuming, labor costs can, according to (Burnham et al., 2021), dominate the TCO.

The economic viability of BETs is further outlined by Bhardwaj and Mostofi (2022), describing that, on a 5-year timeframe, the TCO of best-in-class BETs (160 km) is lower (£0.93/km) compared with the TCO of diesel trucks (£1.01/km), despite factoring in the higher initial purchase price of the BETs. This is also emphasized by Rajagopal et al. (2024), who highlight that BETs can provide major cost savings during their operating time, and a TCO that is lower compared with ICETs after a 5-year timeframe. Moreover, Wang et al. (2024) assert that the initial purchasing price of BETs is around 90% higher compared to ICETs. The importance of spreading out the initial capital expenditure over a long period is also highlighted, thus increasing utilization which is a key factor for reaching economic advantage with BETs.

Wang et al. (2024) describe that the difference in TCO between BETs and ICETs is smaller for heavy-duty trucks (11%) compared with medium-heavy trucks (33%), demonstrating that high vehicle utilization, which heavy-duty trucks are usually associated with, amplifies the advantages of the fuel consumption of BETs. In contrast with these findings, Vijayagopal & Rousseau (2021) describe that larger BETs face more difficulty achieving this compared with smaller BETs, which is explained by the significantly larger battery required on a larger BET.

Furthermore, BETs have simpler drivetrains compared with ICETs and experience less wear and deterioration on the braking system, which is explained by regenerative braking and the absence of a gearbox. As a result, the maintenance cost for BETs is estimated to be one-third less compared with ICETs (Bhardwaj and Mostofi, 2022). This also goes in line with Burnham et al. (2021), describing that BETs have lower maintenance and repair costs compared with ICETs, in relation to the initial purchasing cost of the vehicles.

However, the battery is the major incremental capital cost for BETs and is a significant additional initial cost, compared with ICETs (Bhardwaj & Mostofi, 2022; Rajagopal et al., 2024), indicating that a long-term perspective is necessary when investing in BETs. The long-term perspective is also emphasized by Grauers & Karlsson (2023), as increased demand and production volume in the long run, in combination with technological advancement, will act in favor of the prices of electric trucks.

2.2.2 Routing and queuing issues

Karlsson and Grauers (2024) investigated the market dynamics and interaction between two charge point operators (CPO) and electric trucks, how the charging prices fluctuate based on the utilization level of the chargers, and the risk of queuing during rush hours. The results indicate that the price for fast charging will remain at a reasonable level during rush hours and low outside rush hours. Moreover, the CPOs can maintain profit while the risk of queuing at the charging stations is limited, showcasing that fundamental market principles can provide a well-functioning network of charging infrastructure. Furthermore, the limited risk of queuing at the charging stations is given the assumption that truck operators are willing to "pay the price", i.e., choosing another charging station that has a free spot but charges a slightly higher price.

According to Cheng and Lin (2024), the prolonged operating time for electrical trucks (16-32% longer on average) resulting from the required charging along the way needed to complete the assignment, along with the high initial investment costs associated with electrical trucks, are seen as barriers by fleet operators (customers of BETs). Even though the prolonged operating time is synchronized and optimized for charging during the legally mandated break requirements. Bhardwaj and Mostofi (2022) also describes aspects that customers of BETs are concerned about, which include the time required for the battery to fully recharge, the battery range capability per charge of BETs, and the charging infrastructure, i.e., the availability of charging stations along the way.

2.2.3 Charging infrastructure

Development of the charging infrastructure is a prerequisite for the transition from diesel to electric trucks (Liimatainen et al., 2019). However, the currently low availability of charging infrastructure for BETs makes charging a critical factor for fleet operators, and Wang et al. (2024) emphasize that great efforts must be directed to improve this area to facilitate the transition to fully electrified transportation fleets. Grauers & Gillström (2023) describes four charging strategies: home charging, terminal charging, charging beside the road, and charging at a bypassing facility (e.g., a customer site), all of which have different characteristics and are thus suitable in different situations and circumstances. Home charging is associated with low power, which makes overnight charging common, and this is also when the price of electricity is usually the lowest (Isakov et al., 2023). BETs that return to the terminal where it originated after finishing the deliveries are well-suited to use home charging or charging at the terminal (Grauers & Gillström, 2023).

Conversely, charging beside the road is associated with high power, thus reducing the charging time significantly. This strategy is suitable for long-haul routes or when the driving distance of the route is greater than the range of the truck and charging along the way becomes necessary. The strategy ”charging at bypassing facility“ is, e.g., suitable for BETs where there are drop/pickup locations at a customer site during the route.

Critical factors in determining the optimal charging strategy are weight to volume ratio of the goods being transported, and the electricity price when using public fast charging (Grauers & Karlsson, 2023). Grauers & Gillström (2023) also outline seven factors that can act as enablers or preventers when electrifying a transportation fleet: distance, number of stops, planning horizon, variation in routes, frequency of routes, time of loading and unloading, and returning to the own terminal. The individual factors are important to consider; however, it is the combination and synergies of these factors that finally influence the feasibility of electrification.

Furthermore, these charging strategies are associated with different risks, and they can be categorized into low risk, medium risk, and high risk. Privately owned chargers are associated with low risk since companies have full control over the chargers and the incurred costs. Medium risk includes, for example, contracted public chargers, where the price can be ensured and known for some extended period through contracts with the charge point operator. Public charging is a strategy associated with high risk due to the risks of queuing at charging stations and the risk of high prices for charging if the utilization of the charging stations is low.

There are two types of charging systems, the first is a combined charging system (CCS) that has a capacity up to 400 kW and the second is megawatt charging system (MCS) that is currently being developed and that has a capacity over 1000 kW (1 MW) (ABB, 2025; personal communication ABB, 2025)

2.2.4 Public Charging

To opt for a situation of high prices for electricity from public fast charging, due to low utilization, haulage companies should aim to invest in large batteries to minimize the need to charge at these stations. This situation is, however, described as unlikely by Grauers & Karlsson (2023). Whether using contracted chargers (or owned public chargers) or fully public charging will depend on whether the routes are fixed or constantly varying (Grauers & Gillström, 2023). The initial risks with the electrification of heavy-duty trucks lie in whether one party changes strategy, e.g., if hauler companies switch from smaller to larger batteries, which is negative for charge point operators since this decreases the demand for charging. Conversely, if hauler companies switch to smaller batteries, a price increase in public fast charging could be challenging, since smaller batteries increase the chance of needing to use public fast charging along the way (Grauers & Karlsson, 2023). However, this risk will decrease in the long run due to the competitive environment of electric trucks and charging infrastructure, and as electric trucks become more common, it will yield higher utilization of the charging infrastructure and consequently lower prices for fast charging.

Unterluggauer et al. (2022) highlight a broader perspective and emphasize the collaborative approach when planning the charging infrastructure, which is a coordination between the transportation network (TN) and the distribution network (DN), with the objective of mitigating the grid burden, which is a potential negative consequence of large-scale charging of electric vehicles. Three methods are outlined for optimal placement of charging infrastructure (CI), node-based, flow-based, and agent-based. The node-based approach assumes that the nodes in a transportation network represent charging demand and aims at locating charging facilities within these nodes to meet this demand. The advantage is the simplicity of the model, and the limited amount of data required. However, the simplicity is also its downfall, e.g., it does not consider detours associated with charging activities.

Furthermore, the flow-based approach is a method where the charging infrastructure and the placement of the charging stations center around the flow of traffic, and charging stations are placed where the flow of traffic is the highest, i.e., maximizing the traffic flow through each charging station. Lastly, the agent-based approach is an approach that is efficient at handling randomness, as it considers individual driving patterns and other detailed user data, e.g., where charging is estimated to take place. The charging infrastructure is then aligned with this and is placed at nodes where the frequency of charging opportunities is the highest.

The node-based approach is the most preferable method from the perspective of the required data, followed by the flow-based approach. These methods use aggregated data, conversely to the agent-based approach, which uses data on individual users and driving data, thus entailing higher requirements (Unterluggauer et al., 2022).

2.2.5 Technical features of battery electric trucks

The most common type of battery used in BETs are lithium-ion batteries (Pelletier et al., 2017). The capacity of the battery pack depends on the number of electrochemical lithium-ion cells. Consequently, the weight of the battery increases when there is an increase in cells and battery capacity. This capacity and weight of the battery influence the freight BEVs range and loading capacity. Furthermore, the payload of the vehicle influences the battery's capacity and energy performance. It is however common to approximate the capabilities of the batteries and express their capacity in terms of Wh/kg. As for writing the report, in 2017, the range of lithium-ion batteries are around 100-180 Wh/kg and expected to increase to 500 Wh/kg (Pelletier et al., 2017).

The fluctuation in price in public fast charging is one factor that increases uncertainty and makes it difficult to determine the optimal battery size and charging strategy (Grauers & Karlsson, 2023).

The expected high initial investment associated with a large battery may lead to haulage companies opting for smaller batteries, under the assumption that the prices for public fast charging are at a reasonable level. The size of the battery will also affect the payload capacity, where a large battery will result in less weight being transported, and vice versa. However, the cost of decreased payload because of a large battery will depend on the density of the goods being transported, ranging from almost zero with low-density goods to a very large cost if the goods being transported are of very high density, such as concrete or iron ore (Grauers & Karlsson, 2023). Furthermore, according to Grauers & Gillström (2023), it is optimal from a cost perspective to increase the battery in proportion to the driving distance, however, only up to a critical point, which is estimated to be 250 km. This distance is heavily dependent on the type of transport, e.g., for high-density goods, this critical point will be lower and vice versa. After this critical point, the battery size will negatively affect the payload capacity of the truck and thus reduce profitability. For longer transports, it is more optimal to use public charging than to increase the battery size, which would negatively affect the payload (Grauers & Gillström, 2023).

The state of the battery in freight BETs influences their operational capabilities, where a loss in battery capacity results in a decrease in drivable range. The lifespan of the lithium-ion batteries is limited, and it is influenced by the charging and discharging behaviors, i.e. battery degradation or battery aging. The end-of-life of a battery is usually considered to be when the battery has lost 20% of its maximum capacity, usually lasting five to ten years depending on the situation. Consequently, it is important for fleet operators to minimize degradation and preserve the batteries' capabilities, since it impacts both flexibility and profitability of their vehicles (Pelletier et al., 2017). Even so, Wang et al. (2024) describes that the costs associated with battery degradation, such as increased fuel consumption over the vehicle lifetime, are minimal and have a minor effect on the TCO in general. According to Grauers (personal communication, 2023) the main factors for battery aging are: charge and discharge cycles, i.e., how many times a battery is charged and discharged; temperature; power, where higher charge and discharge power accelerate the aging; and time, as the battery ages over time, even if it is not used. The main effects of battery aging are reduced capacity and maximum power of the battery.

Pelletier et al. (2017) mention that BEVs should be charged as closely as possible to their departure times, since this could increase the battery lifetime by 40%:

> *"For example, since calendar aging occurs faster when the battery is stored at a higher SOC, in terms of battery health, the charging of fleet vehicles should always be performed as closely as possible to their departure time."*

However, this is only possible to do when it does not impede the operational flexibility of the vehicle and fleet. Overcharging degradation should be modeled and included as a cost in the transportation planning problems that route planning tools solve (Pelletier et al., 2017).

Degradation occurs through calendar aging, i.e. the battery degrades when it is not in use and when it is kept in storage. Cycle aging is the other type of degradation, which refers to the loss in capacity due to charging and discharging of the battery. The degradation happens both in terms of driving range, i.e. capacity fade, and in terms of maximum power output, i.e. impedance rise. Factors that accelerate the degradation are e.g., overcharging, high temperature, high SOC (state of charge) during storage, large DOD (depth of discharge), and high charging or discharging rate (Pelletier et al., 2017).

3

Problem discussion

As one of the largest freight and logistics companies, DB Schenker is now faced with the challenge of electrifying their operations. As highlighted in the previous background chapter, this challenge is huge and multifaceted, making it difficult to know where and how to start. Decisions need to be taken on a technical and operational level such as where to start implementing electric trucks, where to install chargers and what capacity the batteries should have. Meanwhile these decisions will be impacted by other actors in the system and could impact other actors in the system as well, e.g. haulers, CPOs, OEMs, or policymakers.

DB Schenker was engaged in a pilot project called E-Charge, where one electric truck is implemented in their line-haul operations. The purpose of this pilot was to "develop, test and demonstrate battery electric long-haul truck transports" and it is set to end this year (2025). This project has given DB Schenker more operational and technical insights into the challenge of electrifying their line-haul operations. However, this pilot project has only covered one route, between Jönköping and Södertälje, and its context and boundary conditions. Hence, the project's findings from this single route cannot be readily generalized to DB Schenker's broader network. Routes across the network differ in terms of parameters such as distance, regional infrastructure, traffic patterns, etc. This variability creates questions like: Which routes are technically and operationally feasible for electrification? Which routes should be prioritized for early implementation? And how do these decisions align with the broader system perspective, considering the interplay between different actors, resources and activities in the transportation system? Consequently, the purpose of this thesis is to examine how line-haul routes of a LSP, such as DB Schenker, differ in terms of feasibility, profitability, and systemic impact when introducing heavy-duty BETs. To achieve this objective, four research questions have been formulated.

3.1 Research questions

The previous research chapter highlighted that the technical feasibility of BETs depends on several factors such as battery capacity, charging infrastructure availability, route characteristics, and operational patterns (Karlsson & Grauers, 2023; Pelletier et al., 2017). Grauers & Gillström (2023) emphasize that the operational schedule and route-specific factors, like distance, frequency, and number of stops, play a critical role in determining whether electrification is viable. Research question 1 (RQ1) aims to identify what influences the technical feasibility of introducing BETs on different routes:

RQ1: *What influences if the introduction of BETs on a line-haul route is technically feasible?*

Furthermore, it is important to consider the economic perspective when introducing BETs and not only if it is technically possible, since the companies need to remain profitable. According to previous research, BETs can offer a lower TCO compared to diesel trucks under certain conditions, but the outcome of these TCO calculations is sensitive to variables such as truck and battery utilization, labor costs, and charging strategy (Burnham et al., 2021; Bhardwaj & Mostofi, 2022; Vijayagopal & Rousseau, 2021). RQ2 and RQ3 therefore seek to examine how profitability differs between routes and which specific cost factors are most influential for the TCO.

RQ2: *How do BETs compare to diesel trucks in terms of total cost of ownership for different types of line-haul routes?*

RQ3: *What are the critical factors that influence the total cost ownership of introducing a BET on a line-haul route?*

In addition to technical and financial concerns, the introduction of BETs in line-haul operations is also influenced by the surrounding transportation ecosystem and business network, as highlighted by both Browne et al. (2022) and Raoofi et al. (2024). The success of electrification depends on the coordination between multiple actors, since the freight transportation system is loosely coupled and resistant to change. Gillström (2024) also describes this system inertia as a barrier that could be overcome by deeper collaborations among the actors. RQ4 is therefore aimed at understanding how the introduction of heavy-duty BETs in line-haul operations is influenced by the surrounding business network and how a transition to BETs will influence the business network.

RQ4: *How does the introduction of BETs in line-haul operations influence the surrounding business network of the transportation system?*

3.2 Limitations

The report will not take into consideration the DSV and DB Schenker merger, since this is set to be complete at the earliest after Q2 2025, which is after this report will be finished. Furthermore, the report will be limited in its case study and calculations, since the focus and purpose of this report is not to go into great detail of each route.

4

Methodology

The following chapter outlines the research methodology of this study, as well as explaining how the research method contributes to answering the research questions. First, the general research method will be described, followed by a more detailed description of each approach in sections 4.1-4.4.

To gain a comprehensive and holistic understanding of the transportation network and the factors influencing the electrification of BETs, a mixed-method research approach was used. Mixed-method research is an approach combining quantitative and qualitative research (Bryman & Bell, 2015, p.641). This research methodology allows the combining of static features from the quantitative approach and processual features from the qualitative approach. More specifically, an embedded design was used, which is an approach of mixed-method used when one method alone (either qualitative or quantitative) is considered inadequate for gaining a thorough understanding of the problem, or if there are multiple research questions that are best addressed using different research methods (Bryman & Bell, 2015, p.646). An illustrative example of the embedded design is shown in Figure 4.1, where our foundation lies in the quantitative research, and subsequently the qualitative research, through which we seek to analyze the broader network perspective (Bryman & Bell, 2015, p 647). The quantitative research, performed through a case study described in more detail in section 4.4, showcasing a static view of profitability and feasibility, and allows for comparability. Meanwhile, the qualitative research consists of a literature study, which provided understanding and insight into previous research and the direction of development, and interviews yielded a view of actors' predetermined notions and perceptions of e.g., the feasibility, barriers, and facilitators for electrification., (Bryman & Bell, 2015, p.652).

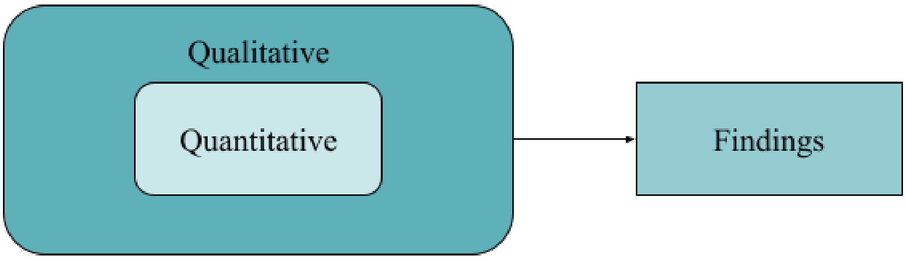


Figure 4.1: Description of the Embedded Mixed Method Design (Bryman & Bell, 2015, p 647).

The different methods used in the mixed-method approach in this case helped address and answer the research questions described in section 3.1. The pre-study and literature review helped address RQ1; the case study and literature review helped address RQ2; the literature review, case study and interviews helped address RQ3; and lastly; RQ4, was addressed through the literature review and the interviews. This is illustrated in Figure 4.2 below.

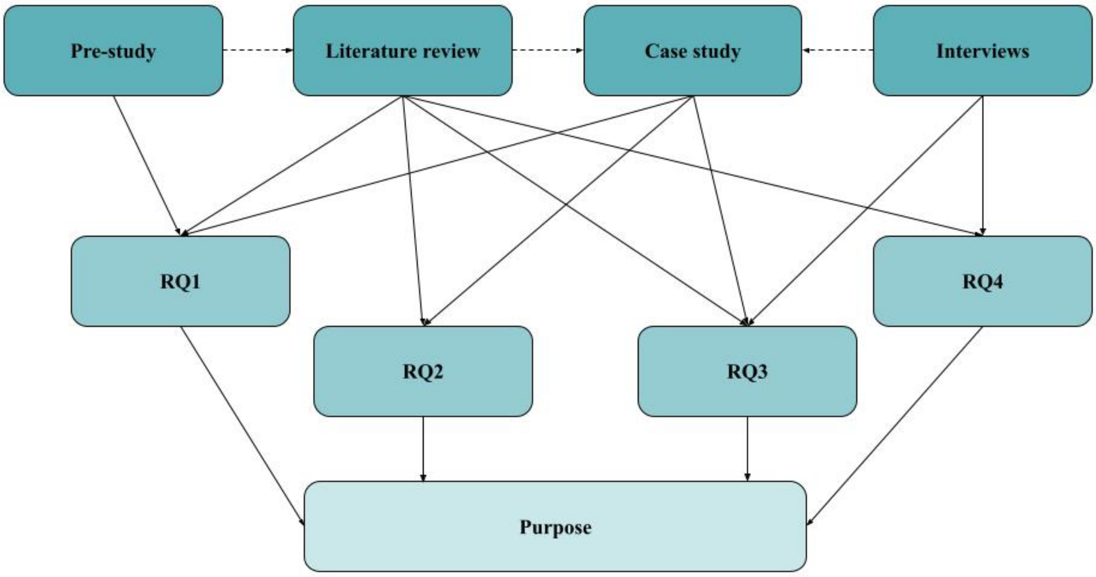


Figure 4.2: How each research method relates to the research questions and the purpose of the thesis.

4.1 Pre-study

A selection of the routes was made during the pre-study, based on the multiple semi-structured interviews with Professor Anders Grauers at Chalmers University of Technology and with professionals at DB Schenker, with extensive knowledge about their transportation network and their ways of working and classifying routes within it. The selection was made so that the routes represent a broader set of routes in DB Schenker's overall transportation network. The selection was also based on the usefulness for DB Schenker to gain a deeper understanding of these specific routes and the broader class of routes that they represent.

The selected routes are listed below, and a more detailed description of the routes is outlined in chapter 7.

Case A

I. Distance: ~80 km
II. Lead time: ~ 1 hour and 30 minutes

Case B

III. Distance: ~630 km
IV. Lead time: ~ 9 hours 30 minutes

Case C
V. Distance: ~ 1125 km
VI. Lead time: ~26 hours

These routes were selected because of their significant differences in characteristics, and introducing electric trucks for these will, consequently, vary significantly. The objective in the selection was to cover many of the factors that can act as enablers or preventers, highlighted in the literature review: distance, number of stops, planning horizon, variation in routes, frequency of routes, time of loading and unloading, and returning to the own terminal.

Additionally, during the pre-study, an electromobility course at PhD-level was studied to deepen the knowledge and expertise within the subject of electrification of heavy duty and long-haul trucks.

4.2 Literature review

A literature review was conducted to lay a foundation for the study. This provided a holistic view of the current state of electrification of BETs, as well as yielding an understanding of the network perspective in the transportation sector and the dynamics and interplay between actors involved in the network. Literature and academic articles for the literature review were gathered from, e.g., Chalmers Library, Google Scholar, and Scopus. Relevant keywords used in searching for literature include battery electric trucks, charging infrastructure, charging strategy, road freight transportation system, and electrification.

4.3 Interviews

Interviews were conducted with multiple actors and stakeholders, such as key individuals at DB Schenker, with knowledge and experience about the electrification of the transportation fleet and the transportation network. This helped define the problem as well as provided insights into the planned case studies and the practical and strategic aspects that DB Schenker will face when electrifying different routes. Furthermore, interviews were conducted with experts and professors in the area of truck electrification and charging infrastructure, and other stakeholders and actors in the transportation network to provide understanding of their interconnectedness. Semi-structured interviews were used, meaning that an interview guide was constructed beforehand, and consisted of relevant questions providing a general structure for the interview. The questions during the interviews did not follow the guide exactly, and additional questions were asked if the interviewee touched upon interesting subjects or areas not included in the interview guide (Bryman & Bell, 2015, p. 481). Snowball sampling method was used, meaning that initial contact was made with relevant individuals with appropriate expertise and knowledge about the subject, and these individuals were used to establish contact with other relevant interview candidates (Bryman & Bell, 2015, p. 728).

The interviews were recorded in accordance with the interviewees consent, and the handling of personal information was in accordance with GDPR (Swedish Authority for Privacy Protection [IMY], 2021). Subsequently, transcriptions of the interviews were performed to have the possibility to go back and analyze what was said during the interviews, thus this provided the possibility to utilize e.g., blockquotes.

4.4 Case study

A case study approach is a popular and commonly used research design in business research since it allows for detailed analysis of the unique settings of the case (Bryman & Bell, 2015, p.67-68). A single case can also sometimes be theoretically generalized to a broader class of cases of similar nature. The goal of a case study, however, is to focus on the uniqueness of the case, and to develop a deep understanding of the complexity of the specific case.

The case study of this report focused on three specific line-haul sub-cases of routes in DB Schenker transportation network. Thus, the case study of this report can be classified as that of a multiple-case study design, since there are multiple cases. This design allows for comparison between the cases and it promotes theoretical reflection on the findings from each case and the cases as a whole (Bryman & Bell, 2015, p.71). On the case specific level, the cases can be described as both intrinsic and instrumental, since the learnings from the cases were both to gain insight into the peculiarities of the specific situations and to understand a broader issue (Bryman & Bell, 2015, p.68). Furthermore, the cases can also be described as both representative and revelatory cases (Bryman & Bell, 2015, p.70). This is because the selected cases are representative cases of the current situation of DB Schenker's transportation network, while the purpose of them are to revelatory examine the opportunities and barriers of introducing electric trucks in these representative conditions. In this report the sub-cases of the three routes A/B/C are henceforth mentioned as case A/B/C or route A/B/C.

Furthermore, data analysis and calculations were made for these routes to estimate the impact, in terms of the cost of introducing electric trucks on these routes. How these calculations and data analysis were conducted is briefly explained here and further developed in chapter 7. These calculations formed the quantitative core of this report, which then acts as a springboard for the discussion and analysis of how the introduction of electric trucks influence the broader transportation network. Simplifications and assumptions were made to make the case study accomplishable during this thesis work, and these assumptions were based on interviews with experts at Chalmers and DB Schenker. These assumptions are further developed and motivated in section 6.3. The plan was to set these boundary conditions instead of looking to optimize these parameters for the individual routes, since the technology is set to change in the future and because the optimal for one route might not reflect the larger class of routes.

To assess the impact of introducing BETs on the different routes, in terms of impact on costs, a quantitative data analysis was made. This is the core of the multiple case study. Data was collected for the different routes, such as the current lead time, general fuel consumption of the current trucks, number of trucks operating on each route, etc. The routes were gathered through reports and data sets internally available at DB Schenker. Consequently, the data itself is not presented in full, to maintain confidentiality. The data was then used to calculate the changes in cost structure and TCO. As previously mentioned, these calculations were based on assumptions and were simplified to fit the scope of this master's thesis, while still broadly representing the general impacts of introducing BETs on these different routes.

5

Theoretical framework

As previously described in section 2.1, it is important to understand the system perspective when analyzing the possibilities for introducing BETs into a logistics system. Raoofi et al. (2024) highlighted the importance of understanding the system dynamics of the transportation system to become more proactive and to improve decision making. Dehkordi et al. (2024) stated that understanding the ecosystem was crucial for developing successful business models for electric freight transport. The barriers and enablers for the transition to electric freight transportation of logistics companies are closely tied to the surrounding ecosystem of actors, according to Gillström (2024). Therefore, it is evident that understanding and analyzing this ecosystem of actors falls within the scope of this research. The transportation system, as described by Browne et al. (2022), consists of multiple actors within its different layers and markets. These actors are influenced by each other and by other external stakeholders, such as policymakers. They govern and utilize different resources to perform their different activities. Consequently, the Industrial Network Approach (INA) has been chosen as a theoretical framework for this research, since it supports analysis of the actors, resources, and activities in the network and the business relationships in which actors in the network are involved (IMP Group, n.d.)

5.1 The network of business relationships in the supply chain

According to Lambert & Cooper (2000), no business is an island but rather part of a larger supply chain network, consisting of multiple actors such as suppliers, customers, distributors and partners. The INA provides a framework to understand the effects and content of long-term interaction among the actors, activities and resources within this network. The individual actors in the network are interdependent on the resources and activities of other actors, making them embedded in a business network consisting of multiple actors (IMP Group, n.d.). Understanding this network perspective becomes crucial, according to Lambert & Cooper (2000), since companies compete on a supply chain and network level, rather than on the business-to-business level. Making it important for a firm to manage the entire network and create efficiency and effectiveness across the whole supply chain to be competitive. This sentiment is shared by Håkansson and Snehota (1995) that suggest that the success of the single firm depends on its position and role within the larger network and not only its own capabilities and business.

Business relationships are what connects the different actors in the network and the competitiveness and profitability of individual companies. These relationships often extend beyond simple transactions, and are instead characterized by mutual orientation, commitment, trust-building, and social exchange over time (Håkansson & Snehota, 1995). Relationships should be viewed as part of a network of interdependent relationships, and not in isolation. Meaning that the relationships are influenced by and influence other relationships, making each relationship embedded in a network of business relationships (Håkansson & Ford, 2002). Håkansson & Snehota (1995) highlight the importance of the concepts of connectedness and interdependence to understand business networks. Connectedness can be seen as the ties that bind companies together in the network and how these are related to each other. Furthermore, the concept of connectedness describes the quality of the relationship, in terms of trust-building and social exchange over time. It explains how changes in a single relationship can impact the state of other relationships in the network, i.e. it describes the mutual reliance of the relationships within the network. The concept of interdependence refers to the interdependence between the different activities, resources and actors in the network. These interdependencies are the substance and content of the business relationships, in terms of actor bonds, resource ties, and activity links in the network. Håkansson & Ford (2002) also state that the performance and effectiveness of are dependent on the direct relationship interactions and on the relationships of their counterparts' relationships with third parties.

The ARA model was presented by Håkansson (1987) as a tool to analyze the interconnected network of business relationships. This framework consists of three dimensions that explain how business relationships are formed, maintained and developed within the network. The first dimension is the actor dimension. An actor can be individual companies, groups of companies, business departments within companies, or individuals. The second dimension, the resource dimension, refers to tangible resources, e.g. raw material, machinery, inventory, facilities, and intangible resources, e.g. human resources, business units within the company and even business relationships themselves. Finally, the activity dimension refers to the activities performed by the different actors in the business network, e.g. production, assembly, transportation, purchasing and selling. These three elements are interrelated with each other in multiple ways, e.g. actors are the ones that perform the activities based on their available resources. Furthermore, each of the different dimensions is related and connected to the surrounding business network, e.g. each individual actor is related to other actors in the network. A basic illustration of the ARA model is presented in Figure 5.1 and the model will be further described in the following subsections.

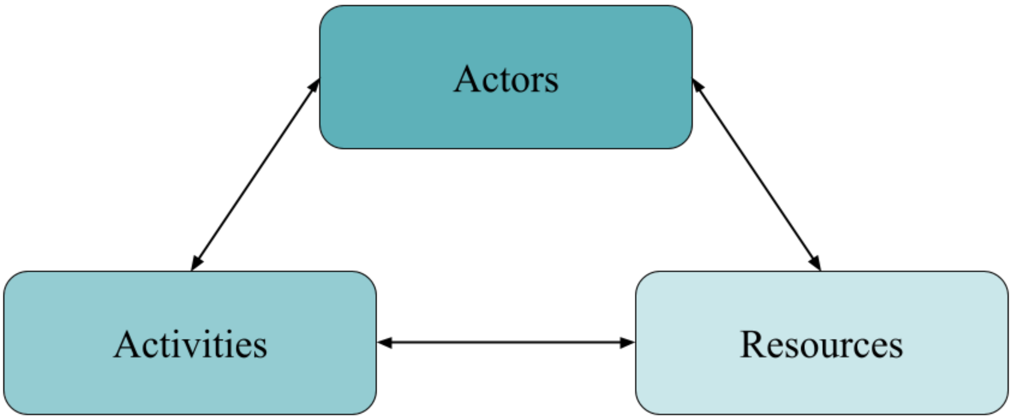


Figure 5.1: A basic illustration of the ARA model, highlighting the interconnections between Actors, Resources and Activities.

5.2 The actor dimension

Actors are, as previously stated, individual people or a group of people who engage in business relationships with other actors in the network to reach their own individual interests or goals (Håkansson & Snehota, 1995). Relating back to the transportation system model of Browne et al. (2022) there are different types of actors in the different levels of the transportation system. In the supply chain layer, you have actor roles such as manufacturers, wholesalers, and customers. In the transportation layer you have actors like LSPs or haulers. In the infrastructure layer you have actors like the Swedish transportation administration (Trafikverket), gas station owners, or charge point operators.

Actors are the ones that perform activities, and they are the ones that govern and control resources by coordinating, combing, organizing, and economising their use, connecting the actor dimension to the other two dimensions of the ARA model (Håkansson & Snehota, 1995). Actors can influence their positions within the network, and they contribute to the overall structure of the network by their interactions with each other, e.g. through interactions and activities such as purchasing, selling, or forming partnerships. The connections between the actors in the network are referred to as actor bonds, illustrated in Figure 5.2. These bonds are shaped by factors such as trust, control, expectations, and shared norms between the actors, and they play a crucial role in determining the strength and stability of relationships within the network. Furthermore, the actor bonds influence how resources are accessed, and activities are coordinated with other actors in the network.

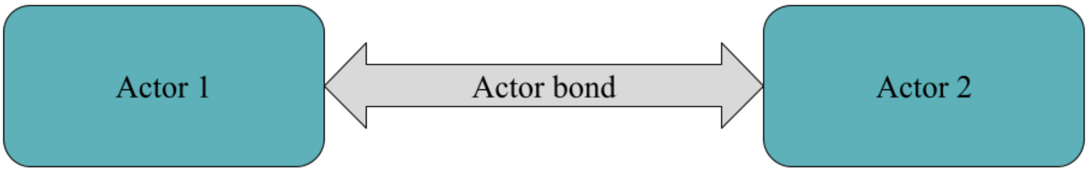


Figure 5.2: Actor bonds connect individual actors with each other.

5.3 The resource dimension

Resources can take various forms, including physical assets such as trucks, human resources such as skilled individuals, and even business relationships themselves (Håkansson & Snehota, 1995). These resources are usually categorized as either a tangible or intangible resource. Examples of tangible resources are infrastructure, equipment, tools, and vehicles. Intangible resources include knowledge, reputation, organizational and individual capabilities. A key characteristic of resources, according to the INA, is that they are heterogeneous, meaning that a resource's value is not fixed but instead dependent on how it is combined with other resources within the network. For example, a truck as a resource can have its utilization increased by having route optimization tools or by having enough drivers to cover for different driving schedules. Furthermore, the resources are not always confined within the strict boundaries of individual actors, since they can be shared, co-developed, or embedded within the relationships themselves. This interconnectedness between a single resource and another, both internally and externally, is described through resource ties, see Figure 5.3. The resource ties are what allows for complementary capabilities, synergies, and enhancement of the overall value generated within the network (Håkansson & Snehota, 1995).

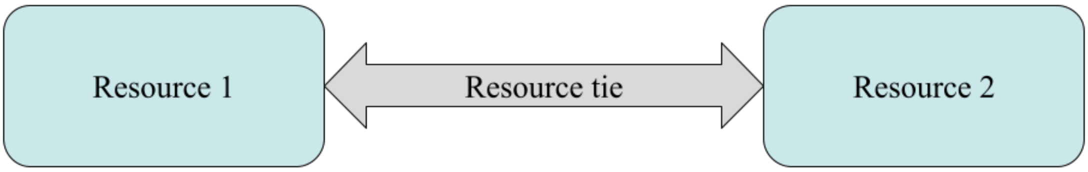


Figure 5.3: Resource ties are the substance/content of business relationships in the resource dimension. Specific resources may be interdependent and connected through resource ties.

5.4 The activity dimension

Activities are the actions that actors perform to create value, which relies on the exploitation and coordination of resources said actors' control (Håkansson & Snehota, 1995). Examples of activities include production, purchasing, marketing, planning, and warehousing, and they may occur sequentially or in parallel with each other. This depends on the network structure and interactions between actors and resources. Value is created in the network through these activities, and the value of each individual activity is dependent on the other activities, actors, and resources in the network. Consequently, the value of a single activity can vary over time in tandem with the dynamic and surrounding business network. For example, a hauler actor may utilize their truck fleet as a resource to create value in terms of transportation. If they transition to electric trucks, some of their activities, such as refueling or maintenance, will change accordingly. These connections of when and how different activities are coordinated are called activity links, see Figure 5.4. These activity links impact and influence the performance and effectiveness of individual activities, while also creating interdependencies across the network.

Figure 5.4: Activity links are the substance/content of business relationships in the activity dimension. Activity links connect interdependent activities with one another.

5.5 The relationship structure

Håkansson & Snehota (1995) mention two concepts for categorizing and understanding business relationships. The first is substance and it relates to what is affected by the relationship in the three layers of actors, resources, and activities in the network. The second concept is function, which relates to who is affected by the relationship. The function of the relationship is split into three different types, the function for the dyad, the single actor function, and the network function.

The function for the dyad refers to how the business relationship between two parties creates a quasi-organization, where integration between the activities, actors, and resources occur through links, bonds, and ties. Allowing for value creation and resource utilization beyond what is possible in isolation, also known as team effects (Håkansson & Snehota, 1995).

Comparatively, the single actor function explains how the relationship affects the individual actors differently. This difference between the actors can give rise to tension and conflict in the relationship, especially if the companies have different goals. The ability to exploit the previously explained dyadic function is what explains the ability for the individual company to influence its performance potential, since it allows for changes in their organisational structure, collection of resources, and activity structure. How well they can exploit the dyadic function depends on the quality and properties of the relationship between the two parties, i.e. the actor bonds, resource ties, and activity links (Håkansson & Snehota, 1995).

Finally, the network function refers to how a change in a relationship between two parties can influence other parties and relationships in the network. It is possible for third parties to adjust their own relationships to influence this change in the network, such as exploiting, promoting, or working against this change. Consequently, the network as a whole has its origin in and development from the relationship between the web of actors, the resource constellation, and the activity patterns (Håkansson & Snehota, 1995).

Håkansson & Snehota (1995) describe the ARA model's scheme of analysis as a conceptual framework for analysis as well as a heuristic way of managing relationships, as illustrated in Figure 5.5. The framework makes it possible to identify how different factors influence the relationships in the network and how a change in the parameters affects the relationships. Helping to identify and understand the relationship developments and changes in the network and the effect it could have on different actors. This in turn allows for predictions of potential reactions from actors in the network and when to intervene in relationships to achieve some desired effect, helping to manage the relationships. It allows for an analysis of the effects on cost-revenue parameters for the individual companies involved, the first column in Figure 5.5. It can also help analyze the direct effects on the relationship potential between companies, the second column in Figure 5.5. Furthermore, it also allows for an analysis of indirect effects on the overall network structure, the column in Figure 5.5. To summarize, the framework allows for structured evaluations of the state of relationships in the network, analyzing potential changes in the relationships in the network, and in helping locate critical issues to allow for better management of the relationships in the network.

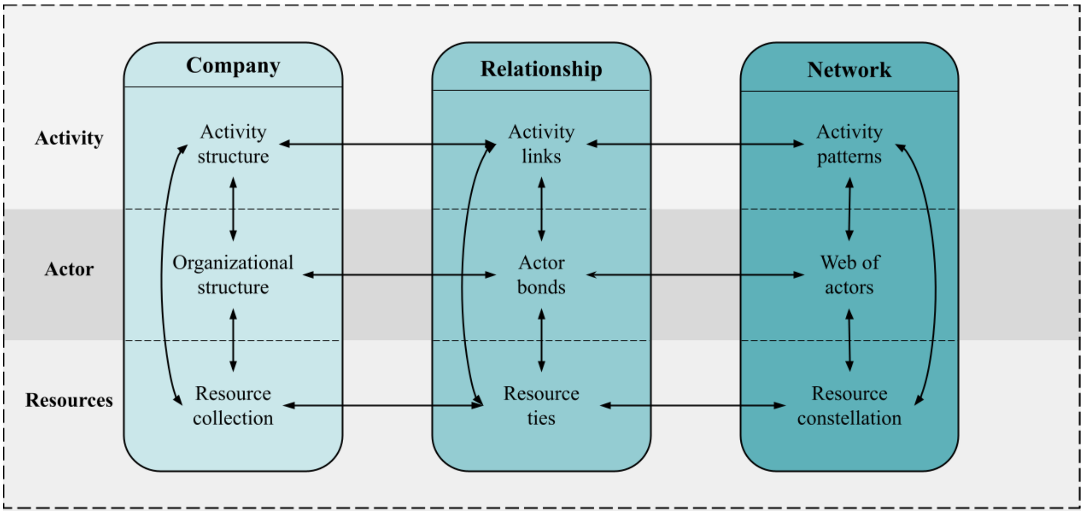


Figure 5.5: An illustration of the ARA scheme of analysis presented by Håkansson & Snehota (1995).

5.6 The actors, resources, and activities in the transportation system

In the transportation system, there are multiple actors involved that control different resources and coordinate multiple activities with each other, to facilitate the transportation needs of the supply chains. The truck is one central resource that is controlled and owned by the haulers, and it is the truck that facilitates the activity of transporting goods on the roads, with roads being another resource needed to facilitate the transport. The need for transportation comes from the customers of the haulers, with one large type of customer being LSPs that offer logistics services, including transportation management, warehousing, freight consolidation, and distribution solutions, to the end customers of the transportation service. The LSPs own and control resources such as terminals, trailers, and the actual relationship with the end customer. The LSPs perform activities such as coordinating and consolidating transportation flows, managing warehousing operations, organizing cross-docking activities, and optimizing truck utilization. In the current system, the trucks are reliant on the resource of fuel, which is usually provided by “gas station actors”. The trucks themselves are also produced by OEM actors. By switching the truck resource from an ICET to a BET, it will have a ripple effect on the relationship structure and content between the actors, resources, and activities in the system. It will cause changes among the actors; some actors might be excluded from the system, some new actors will enter the system, and some current actors will be replaced by new ones. This is the change that will be analyzed in chapter 9 of this report, based on the INA.

6

TCO calculations: Starting points & Assumptions

This chapter outlines the framework used for calculating the TCO of an electromobility system, which depends on the design of the electromobility system in terms of battery capacity and charger capacity. The first section of this chapter outlines how the TCO is calculated for a mobility system. The second section outlines how to appropriately size the battery and the chargers for each route. The final, and third, section presents the assumptions and input data used for the calculations of the electromobility system of each case presented in chapter 7.

There are several ways to calculate total cost of ownership (TCO), depending on which cost parameters are included. Likewise, the sizing of batteries and chargers can vary based on different priorities and assumptions. Therefore, the calculations in this report should be viewed as a proof of concept, not as the definitive method, for assessing whether a route is technically feasible to electrify, if it is economically viable, and what factors influence its profitability.

6.1 Calculating the total cost of ownership

For a transition to BETs in line-haul operations to be feasible they need to be economically viable. The operating cost of the BET needs to be lower compared to diesel trucks, since this is seen as one of the main cost benefits of BETs. As previously mentioned, a transition to BETs will require a change in the surrounding system, which is currently adapted to ICETs. To fully compare these two systems a total cost of ownership needs to be performed for both systems, so that their respective TCOs can be compared. According to Bladh & Ström (2008), the TCO can be split into the following costs: acquisition costs (fixed), operating costs (variable), and the end-of-life costs. This report will also include the indirect cost that relates to losses in operational flexibility. The relevant cost of each cost category will be explained in the following subsections.

6.1.1 Acquisition costs

The acquisition costs are the upfront and fixed expenses related to the mobility system. These costs include: the truck purchase price, the cost for the battery for a BET, and the cost for charging infrastructure in terms of the actual charger as well as a grid connection and potentially the purchase of land for housing the charger. These fixed costs are usually depreciated over time and need to be adapted to the set investment horizon, meaning that these costs have different depreciation horizons and they need to be adapted for the set investment horizon of the TCO. E.g. the investment for grid connections might be depreciated over a longer period compared to the trucks and chargers. One of the main drawbacks of BETs is the increase in acquisition costs compared to ICETs. In this report's TCO calculations, the only acquisition cost used for the ICET system is the cost of the truck. Comparatively, the acquisition costs used in this report for the BET system are the truck cost, battery cost, charger cost, grid connection cost, and the cost for land to place the chargers.

The acquisition cost of the charger depends on the number of trucks that will utilize the charger, since multiple trucks can utilize the same charger. The TCO will be calculated based on chargers and trucks with a service life of seven years and the calculations will be based on the TCO of a single truck. The cost of the charger also depends on its type, i.e. whether it is a CCS charger or a MCS charger. The acquisition cost of a charger is thus calculated according to equation 6.1.

$$\text{Charger cost per truck} = \frac{\text{Charger type} \times \text{Charger Capacity}}{\text{Number of trucks utilizing the charger}} \tag{6.1}$$

The grid connection has a longer service life (28 years) compared to the service life of the charger and truck (seven years). The grid connection cost is also split on the number of trucks that utilize the charger and consequently also the grid connection. The acquisition cost for the grid connection in the TCO of a single truck is calculated according to equation 6.2.

$$\text{Grid connection cost per truck} = \frac{\left(\frac{\text{Cost of grid connection}}{\text{Grid service life}}\right) \times \text{Truck service life}}{\text{Number of trucks utilizing the charger}} \tag{6.2}$$

It is also possible that installing the chargers will require land, creating an acquisition cost for acquiring and preparing land, which is location specific. This report will classify the cost of acquiring land into two categories, either the cost of purchasing and preparing land adjacent to the land already owned by DB Schenker at their terminals or the cost of purchasing and preparing land elsewhere. It is assumed to be cheaper for DB Schenker to purchase and prepare land at their current locations. The cost of land per truck is calculated according to equation 6.3.

$$\text{Land cost per truck} = \frac{\text{Price of land per year} \times \text{Truck service life}}{\text{Number of trucks utilizing the charger}} \tag{6.3}$$

6.1.2 Operating costs

The operating costs are the daily and variable expenses connected to the mobility system, such as the cost of fuel, energy, drivers, and maintenance. These costs are related to the actual usage and the operations, meaning that their costs will increase together with usage. One of the main advantages with BETs is the assumption that their operating costs will be lower compared to ICETs. In the following calculations of this report, the operational costs included for the ICET system are the cost for the diesel fuel, the cost of maintenance, and the cost of the driver. Similarly, the operational costs for the BET system also include the cost of maintenance and the cost of the driver. For the BET system the cost of fuel is replaced by the cost of energy and the grid fee.

The cost of diesel fuel is usually described in kr / liter, but to simplify the TCO calculations it can be transformed into kr / kWh, similarly to the cost of energy of a BET. A diesel engine typically has 40% efficiency, i.e. it converts 40% of the energy stored in the diesel fuel to forward kinetic energy of the vehicle. The typical diesel fuel contains 10 kWh of energy per liter fuel. The diesel price can thus be converted to kr / kWh according to equation 6.4.

$$\text{Diesel price (kr/kWh)} = \frac{\text{Diesel price (kr/liter)}}{\text{Diesel energy (kWh/liter)}} \times \text{Diesel engine efficiency (\%)} \tag{6.4}$$

With the cost of diesel fuel expressed in kr / kWh and the energy price also expressed in kr / kWh, the total cost for diesel fuel or electric energy can be calculated for each route according to equation 6.5.

$$\text{Total cost of energy (kr)} = \text{Cost of energy (kr/kWh)} \times \text{Total energy required (kWh)} \tag{6.5}$$

Where the total energy required for the TCO's planning horizon is given by equation 6.6.

$$\text{Total energy required (kWh)} = \text{Total distance (km)} \times \text{Energy consumption (kWh/km)} \tag{6.6}$$

Where the total distance is:

$$\text{Total distance (km)} = \text{Distance per route (km)} \times \text{Times driven per year} \times \text{Service life} \tag{6.7}$$

For BETs another cost is the grid fee, which refers to the annual cost charged for the connection to the electricity grid based on the power capacity (in kW) reserved for the chargers. The total grid fee in the TCO calculations, with a planning horizon equal to the service life of the truck, is expressed by equation 6.8.

$$\text{Total grid fee} = \frac{\text{Grid fee (kr/kW/year)} \times \text{Charger size (kW)} \times \text{Service life}}{\text{Number of trucks utilizing the charger}} \tag{6.8}$$

6.1.3 Indirect costs

The indirect costs are the cost of losses in the system, which otherwise could have been utilized to generate profit. In the transportation system there are multiple indirect costs, such as waiting time for the drivers during loading or unloading, the cost of an unused truck, and downtime due unexpected events. This report will only include the indirect cost of extra waiting for the driver and truck, when the BET needs to charge unexpectedly, since the other indirect costs will be present in the ICET system as well, simplifying the comparison. The indirect costs are calculated according to equation 6.9 and 6.10.

$$\text{Indirect driver cost} = \text{Driver salary (kr/h)} \times \text{Time spent waiting (h)} \tag{6.9}$$

$$\text{Indirect truck cost} = \text{Truck waiting cost (kr/h)} \times \text{Time spent waiting (h)} \tag{6.10}$$

6.1.4 End-of-life cost and revenue

The end-of-life costs are the expenses related to handling the different components of the transportation system when they have reached their end-of-life. It is possible that components generate revenue instead of costs at their end-of-life if it is possible to sell the component or if it is possible to find another use case for it, beyond its planned life cycle. An end-of-life cost could for example be that batteries need to be replaced by new ones and it might be costly to dispose of the batteries in order to meet environmental compliance standards. However, it is also possible that a battery could find another use case that goes beyond its planned usage as a battery for a truck, which instead makes it a potential revenue source. Although these components can't find a new use case forever, the planning horizon of the TCO and the way you plan to use the components after this horizon impacts whether it will be an end-of-life cost or revenue. In this report's TCO comparison, the end-of-life revenue of the trucks, batteries, and chargers will be included. These are calculated according to their residual value, i.e. as a percentage of the acquisition cost of the truck, battery, and charger, as described by the following equations.

$$\text{Truck end-of-life value} = \text{Total truck price (kr)} \times \text{Truck residual value (\%)} \tag{6.11}$$

$$\text{Battery end-of-life value} = \text{Total battery price (kr)} \times \text{Battery residual value (\%)} \tag{6.12}$$

$$\text{Charger end-of-life value} = \text{Total charger price (kr)} \times \text{Charger residual value (\%)} \tag{6.13}$$

6.2 Battery and Charger sizing

When deciding on the size of the batteries, it is important to make sure that it will manage to operate the duties the organization offers and performs on a daily basis, and preferably with a margin in order to have flexibility to adapt to changes in e.g., route planning and changes in distances, as well as having a sufficiently long life, considering the deterioration of the battery, in order to be economically viable.

The capacity specified by the manufacturer refers to the gross capacity of the battery, and this capacity is not available for the consumer. Instead, the capacity that is available for the consumer is the nominal capacity which is 80% of the gross capacity (A. Grauers, personal communication, 2023) Furthermore, the end-of-life of a battery is considered reached when the nominal capacity has diminished to 80 % of the nominal capacity (Etxandi-Santolaya et al., 2024; Upadhya et al., 2024). This margin of 20% can be seen as a safety margin during the truck's lifetime, for unforeseeable days with unusually higher energy consumption. This margin of 20% will gradually decrease to zero, and the truck is then considered to have reached the end of its operational life. Hence, if a battery has a gross capacity of 1050 kWh then 20% is unavailable for use; resulting in a nominal capacity of 840 kWh. By further subtracting 20% from this nominal capacity, the end-of-life capacity of the battery becomes 672 kWh. In total the end-of-life capacity becomes 64% of the gross capacity. Figure 6.1 illustrates the battery´s gross capacity in relation to the nominal and EoL capacity.

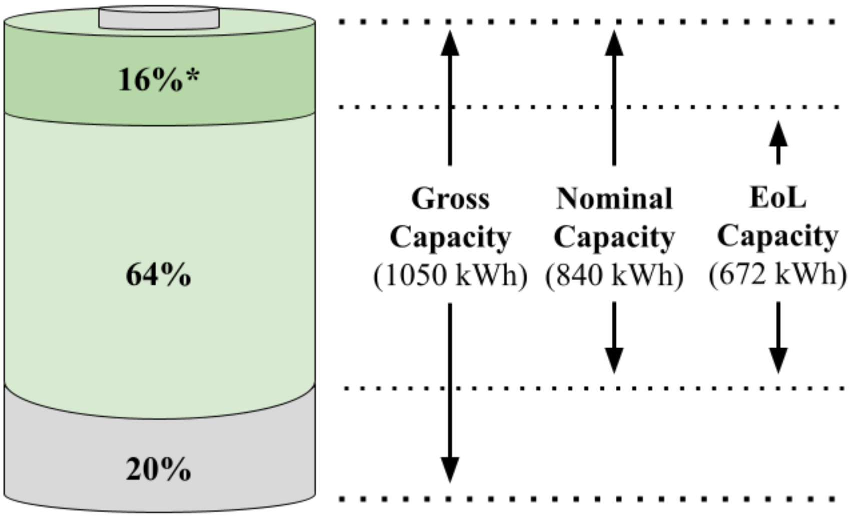


Figure 6.1: An illustration of the battery capacity in terms of gross, nominal, and end-of-life capacity. * 20% of nominal capacity = 16% of gross capacity (20% × 80% = 16%).

The process of determining the size of the battery includes analyzing the routes the truck will operate on, subsequently finding the longest sub-distance within the route, which is thus the distance that requires the most energy, and therefore the size of the battery is adapted to manage at least this route, including a safety margin of 10%. A smaller battery can be compensated by faster or more frequent charging, and vice versa. By adapting the battery size based on its end-of-life capacity, it is dimensioned according to the ”worst scenario”, thus ensuring it will manage the operation requirement throughout its lifetime.

Moreover, when determining the size of the chargers, the chargers are sized based on the length of the breaks, ensuring that the truck can either charge fully, or just enough to manage the next sub-distance with the predetermined margin of 10%. Additionally, the size of the battery also limits the charger size, and a battery can in general be charged with twice the power of the battery, e.g., a battery with a power of 100 kWh can be charged with a power of 200 kW (A. Grauers, personal communication, 2023). Thus, this factor is also considered when determining the size of the chargers.

In the process of determining the battery and charger sizes, an energy distribution diagram helps illustrate the dispersion of the energy consumption during one day of operation. More specifically, it provides a holistic overview of the consumption, thus visually illustrating when charging should take place, the cycle depth, and the required charging capacity during these occasions. An example of an energy balance diagram is illustrated in Figure 6.2. The energy of the battery is displayed on the y-axis, and the operation time of the vehicle on the x-axis.

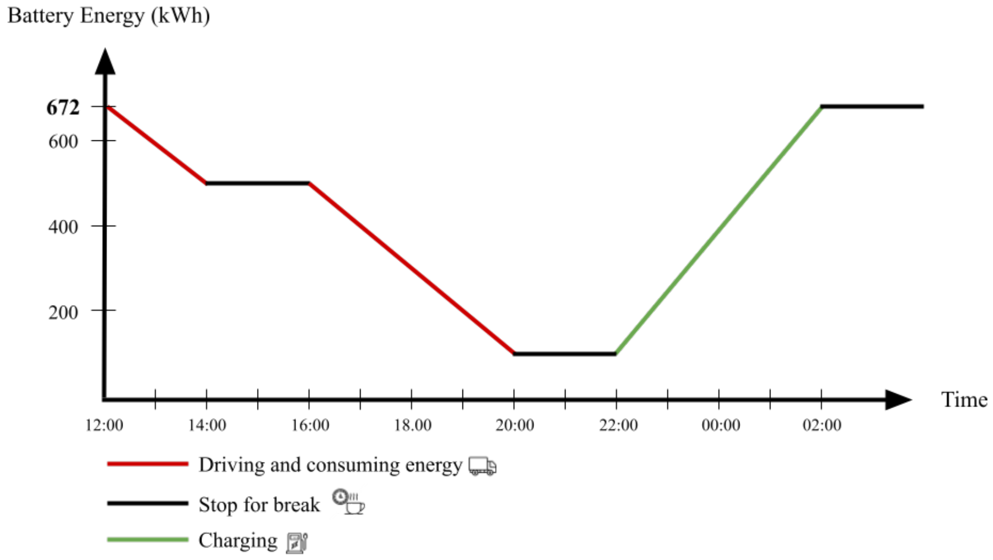


Figure 6.2: An example of an energy balance diagram illustrating energy consumption and charging.

By not using the full nominal capacity every time the battery is charged, one can increase the total energy throughput during the battery's lifetime, i.e., extending its lifespan. This is achieved because a battery manages more smaller charging cycles, compared with fewer larger cycles. The amount of energy charged in relation to the nominal capacity is referred to as the Usable State of Charge (SoC) window. This has economic consequences, since a smaller SoC window used leads to more energy being delivered during the battery's lifetime, thus lower cost per kWh for the battery. Moreover, this SoC window is also important to consider when sizing the battery, by choosing a larger battery than the minimal requirements for the operation, in order not to be forced to charge the battery fully every time. However, the SoC window is not explicitly considered in the calculations in chapter 7, as the calculations mainly serve as proof of concept rather than a precise analysis.

6.3 Data and Assumptions used in the following calculations

The calculations in this report are built on multiple assumptions and simplifications, such as the future state of batteries and chargers being considered, meaning that the capacity of the batteries and chargers used in the case may not be available today, but in the near future. This includes that MCS chargers are well established and do not create any boundaries.

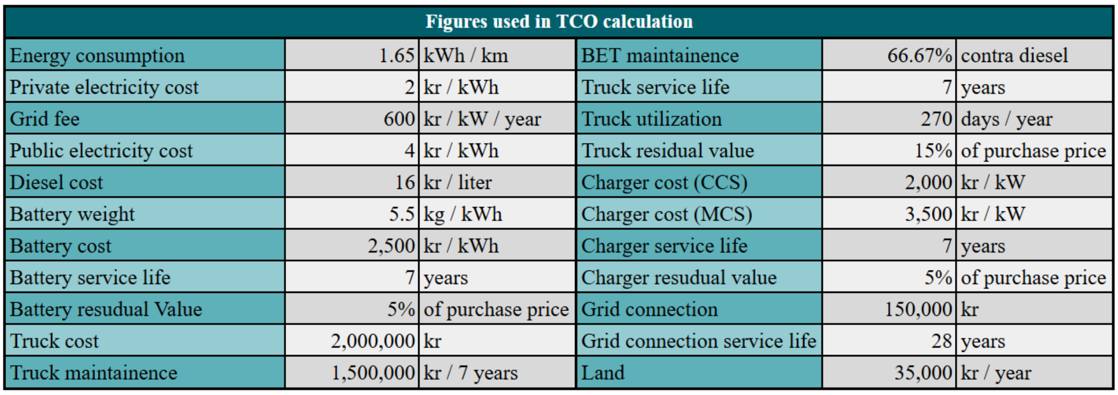
In the TCO, the cost for MCS chargers is considered slightly more expensive compared with CCS chargers, which may not be the case in the future, likely, these will cost the same as CSS chargers. Additionally, the price of the batteries and chargers increases linearly with the size. Another assumption for simplifying the calculation is that the truck and trailer costs the same for both diesel and electric trucks, i.e, 2 MSEK. The trucks operating the route are assumed to have 1 hour prior the scheduled start to charge, and all trucks are fully charged when they start operating. After completing the route, the trucks have 1 hour to charge before beginning the second shift, which is assumed to be a distribution route of approximately 300 km. This distance is manageable even when the battery has reached its end of life, considering an EoL capacity of 672 kWh, resulting in more than 400 km with an assumed consumption of 1.65 kWh/km.

Moreover, the TCO-calculation does not consider the cost of capital since there is no known internal discount rate. The calculations instead aim to show a proof of concept and cost savings in the system in general, rather than how a single actor in the system is affected by such a transformation. It is also a proof of concept regarding which routes are suitable for introducing electric trucks as well as highlighting how future changes in the different variables will impact the outcome of the TCO.

The energy consumption in the calculations is assumed to be 1.65 kWh/km, and this assumption is based on the weight of the trucks. The current diesel trucks operating routes A-C in the cases have an average gross weight of 33 tons. A battery weighs approximately 5.5 kg per kWh of energy stored in the battery (Scania, n.d.; Volvo Group, n.d.). Adding the weight of a 1050 kWh battery results in a total gross weight of approximately 40 tons. For reference, Volvo Trucks has showcased a 40 ton truck with consumption of 1.1 kWh/km, when driving 343 km and averaging a speed of 80 km/h (Volvo Trucks, 2022). Thus, by using an energy consumption of 1.65 kWh/km for the calculations, it accounts for unforeseeable days with higher energy consumption than normal e.g., days where external factors such as cold weather affect the energy consumption negatively.

Land rent for the chargers can vary a lot. In urban logistic hubs it is very expensive, whereas the cost at private property, such as terminals, is low or considered as an opportunity cost. The locations where the chargers are placed in the case are not close to urban logistics areas, therefore the cost can be assumed to be in the lower range, estimated at 35 000 kr/year. Lastly, the private electricity cost is assumed to be 2 kr, where tax and overhead costs are included, and grid fee is 600 kr/kW/year. Important to note is that there are figures used in the case that can vary a lot, and may change significantly over a short period of time, such as the cost of electricity and diesel. There are also figures about which there is much uncertainty, such as the EoL capacity, the battery residual value, and the cost of land. All the figures used in the calculations in chapter 7 are presented in Table 6.1, which were decided upon together with representatives from both DB Schenker and Chalmers.

Table 6.1: Figures used in the TCO calculations.



Figures used in TCO calculation					
Energy consumption	1.65	kWh / km	BET maintainence	66.67%	contra diesel
Private electricity cost	2	kr / kWh	Truck service life	7	years
Grid fee	600	kr / kW / year	Truck utilization	270	days / year
Public electricity cost	4	kr / kWh	Truck residual value	15%	of purchase price
Diesel cost	16	kr / liter	Charger cost (CCS)	2,000	kr / kW
Battery weight	5.5	kg / kWh	Charger cost (MCS)	3,500	kr / kW
Battery cost	2,500	kr / kWh	Charger service life	7	years
Battery service life	7	years	Charger resudual value	5%	of purchase price
Battery resudual Value	5%	of purchase price	Grid connection	150,000	kr
Truck cost	2,000,000	kr	Grid connection service life	28	years
Truck maintainence	1,500,000	kr / 7 years	Land	35,000	kr / year

7

Results: Route cases

This chapter presents the results of the case study, with each route discussed in a separate section. Each subsection includes a description of the route, the rationale behind the charger sizing, and the corresponding TCO calculation.

7.1 Case A

On Route A, the trucks operate between Terminal A1 (T.A1) and Terminal A2 (T.A2), and completes four trips per night, five times a week. One charger with a power of 594 kW is required to fully charge the truck at Terminal A1. The TCO calculation shows that the route is not profitable with 1-3 trucks operating the route, resulting in 4.5 MSEK, 2.1 MSEK, and 1.3 MSEK higher costs compared with diesel trucks. Figure 7.1 shows a schematic illustration of Route A, and more details regarding these results are outlined in subsections 7.1.1-7.1.3.

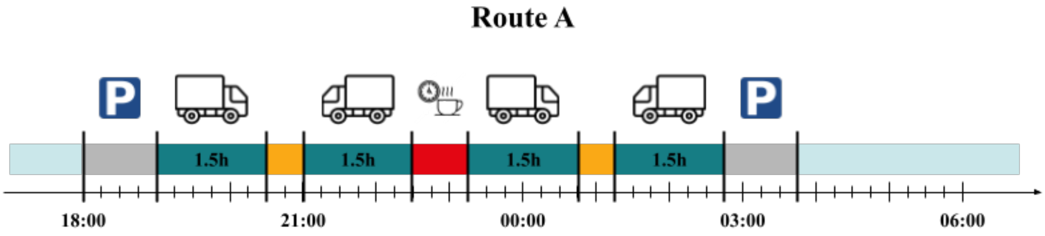
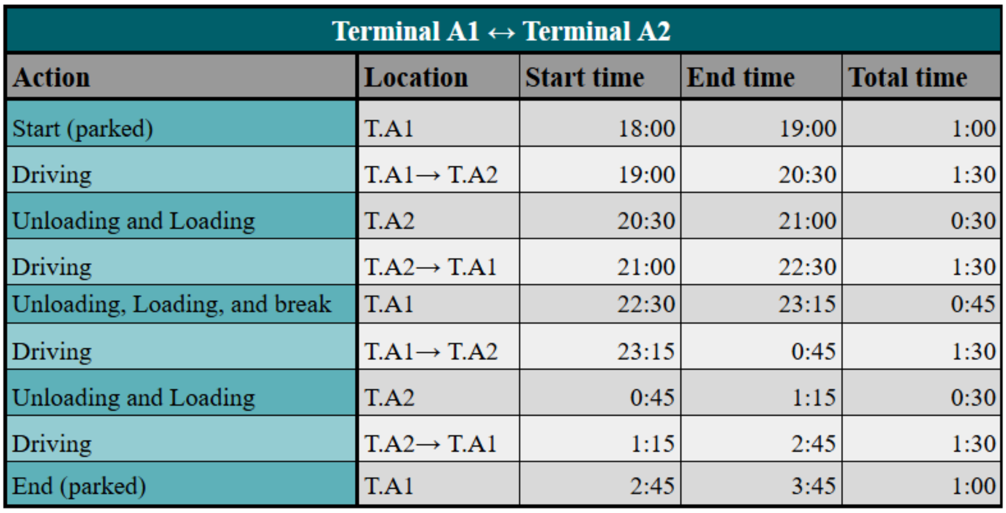


Figure 7.1: Schematic illustration of Route A, Terminal A1 - Terminal A2.

7.1.1 Description of route

Route A, between Terminal A1 and Terminal A2 is the shortest route among the studied routes, and has a distance equivalent to 80 km one way. During one shift, the truck drives back and forth two times, thus resulting in a total distance of 320 km. The truck departs from Terminal A1 at 19:00 and arrives at Terminal A2 at 20:30, with a lead time of 1 hour and 30 min. When at Terminal A2, the truck stands still for 30 min due to loading and unloading, before its departure at 21:00, and drives back to Terminal A1, arriving at 20:30, with a similar lead time of 1 hour and 30 min. Back at Terminal A1 the driver has a break of 45 min while the truck is unloaded and loaded again, in order to be ready for departure at 23:15, and 1 hour and 30 min later arriving at Terminal A2 at 00:45. The truck stands still an additional 30 min during loading and unloading, until it is ready to drive the final distance back to Terminal A1, departing 01:15 in Terminal A2 and arriving at 02:45 in Terminal A1. The departure and arrival times are illustrated in Table 7.1, and the route is driven every weekday.

Table 7.1: Lead times for Route A



Terminal A1 ↔ Terminal A2				
Action	**Location**	**Start time**	**End time**	**Total time**
Start (parked)	T.A1	18:00	19:00	1:00
Driving	T.A1→ T.A2	19:00	20:30	1:30
Unloading and Loading	T.A2	20:30	21:00	0:30
Driving	T.A2→ T.A1	21:00	22:30	1:30
Unloading, Loading, and break	T.A1	22:30	23:15	0:45
Driving	T.A1→ T.A2	23:15	0:45	1:30
Unloading and Loading	T.A2	0:45	1:15	0:30
Driving	T.A2→ T.A1	1:15	2:45	1:30
End (parked)	T.A1	2:45	3:45	1:00

7.1.2 Charger sizing

Figure 7.2 demonstrates the energy consumption and charging of the truck operating on Route A, between Terminal A1 and Terminal A2. After completing the operation, the truck has 12 % battery remaining. The charging takes place at Terminal A1, and to charge fully during 1 hour, a charger with power of 594 kW is required.

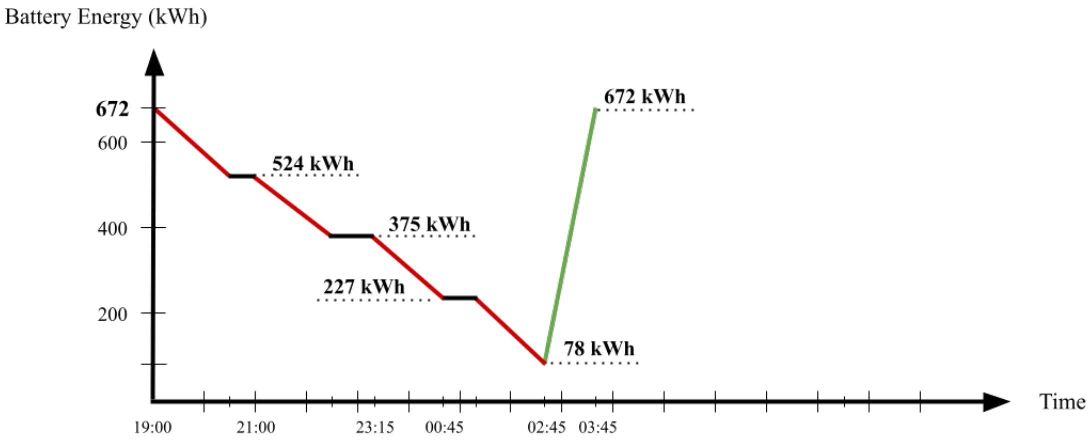


Figure 7.2: Energy balance diagram illustrating energy consumption and charging for Route A, Terminal A1 - Terminal A2.

Table 7.2: Charger size for Route A, Terminal A1 - Terminal A2.

Charger location	Terminal A1
Charger capacity	594 kW

7.1.3 Total cost of ownership for Route A

When calculating the total cost of ownership for the lifespan of seven years for a truck with a battery of 1050 kWh and a single 594kW charger for Route A, the acquisition costs become roughly three times larger for the electric truck compared to the diesel truck. The operational costs are lowered by roughly 10% due to the lower costs of electricity compared to diesel. There are no indirect costs for both systems since the electric system does not need any extra waiting for charging.

When it's only one truck that carries the costs for the charging infrastructure, the TCO for the electric system is 4 500 780 kr less profitable than the diesel system. By increasing the utilization of the charger to two trucks the loss is reduced to 2 072 630 kr, and if three trucks split the cost associated with the charger the difference reduces to 1 263 247 kr, over the seven years. The result is presented in the graph below, where dark blue represents the acquisition costs after the residual EoL value is subtracted, light blue represents the operational costs, and red represents indirect costs. The costs for these four scenarios are presented in Table 7.3 and Figure 7.3.

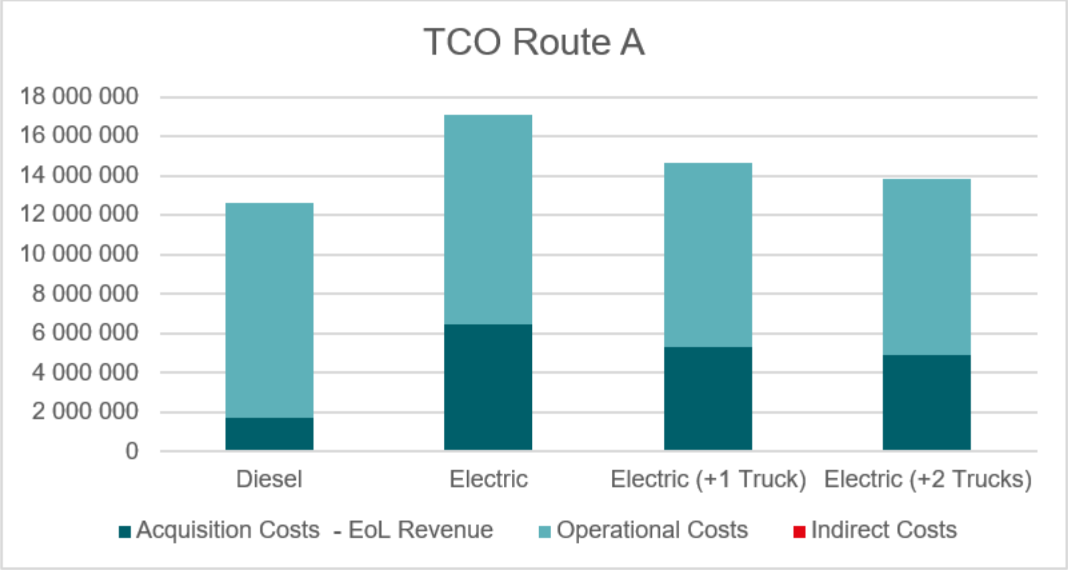


Figure 7.3: TCO for Route A Terminal A1 - Terminal A2.

Table 7.3: Total cost of ownership for the diesel system contra electric system for Route A

Costs	Diesel	Electric	Electric (+1 truck)	Electric (+2 trucks)
Aquisition costs	2 000 000 kr	6 986 500 kr	5 805 750 kr	5 412 167 kr
Operational costs	10 885 740 kr	10 635 220 kr	9 387 820 kr	8 972 020 kr
Indirect costs	0 kr	0 kr	0 kr	0 kr
End-of-life revenue	300 000 kr	535 200 kr	535 200 kr	535 200 kr
Total Cost:	***12 585 740***	***17 086 520***	***14 658 370***	***13 848 987***
Difference:	**-**	***-4 500 780 kr***	***-2 072 630 kr***	***-1 263 247 kr***

7.2 Case B

On Route B, the trucks operate between Terminal B1 (T.B1) and Terminal B2 (T.B2), with a trailer swap at Stop B (S.B), and completes one trip per day, five times a week. Two trucks are therefore needed to handle this transportation assignment. At Stop B, one charger with a power of 559 kW is required, and 620- and 622-kW chargers at Terminal B1 and Terminal B2 respectively. The TCO calculation shows that two BETs operating the route are 9.8 MSEK more expensive compared with diesel trucks, and the loss reduces to 1 936 288 if four trucks share the infrastructure. Figure 7.4 shows a schematic illustration of Route B, and more details regarding the aforementioned are outlined in subsections 7.2.1-7.2.3.

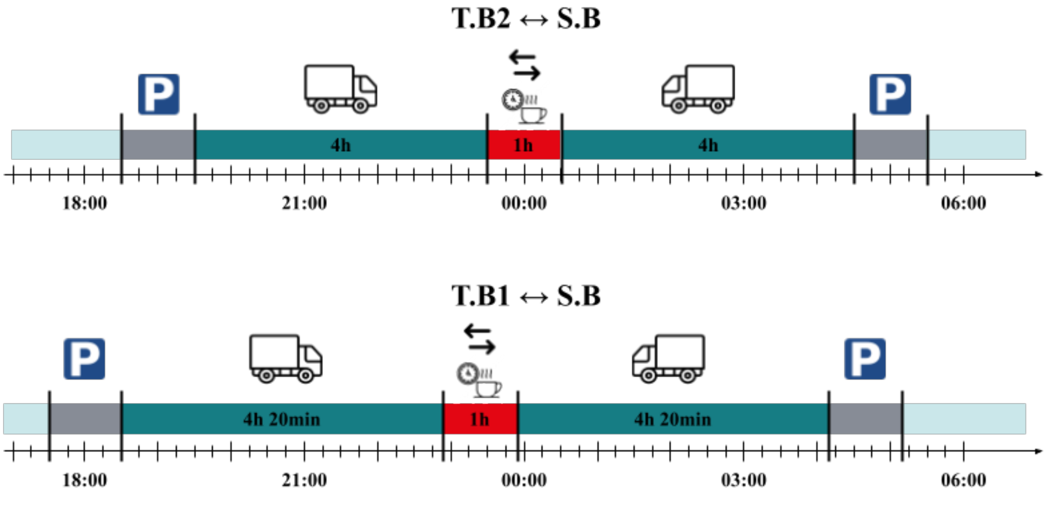
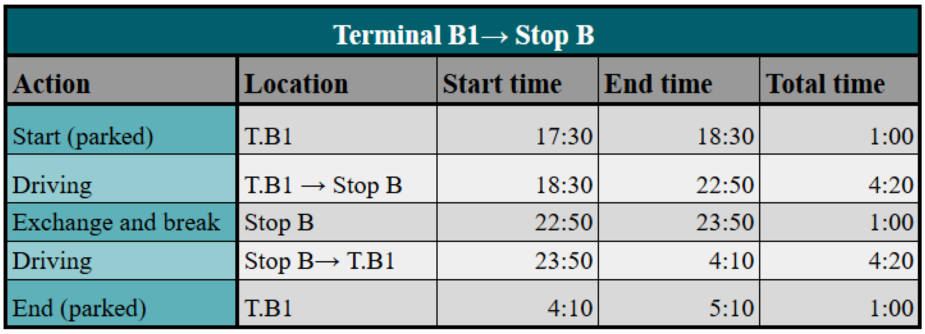


Figure 7.4: Schematic illustration of Route B, Terminal B1 - Terminal B2.

7.2.1 Description of route

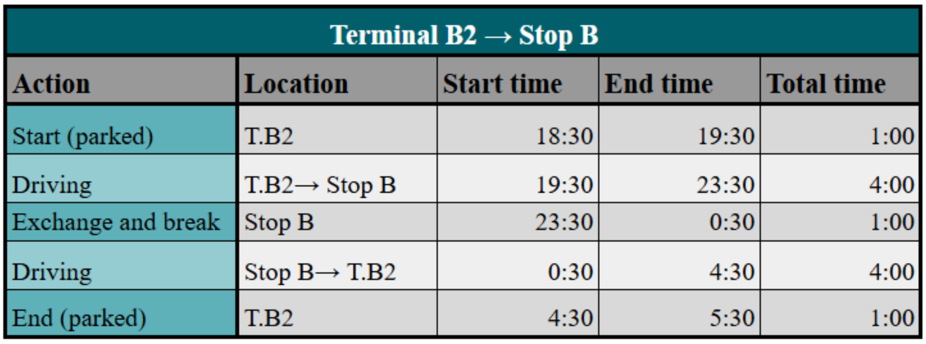
Route B, between Terminal B1 and Terminal B2, has a total distance equivalent to 620 km. The route is scheduled such that one truck departs from Terminal B1 at 18:30, and another truck from Terminal B2 at 19:30. These trucks then intersect at Stop B where a truck swap is performed, meaning that the trucks exchange trailers with each other, and subsequently, after the required 45 min break, return from where they originated. The truck from Terminal B1 returns at 23:50, and the truck from Terminal B2 at 00:30, resulting in a lead time of 9 hours, and 9 hours and 40 min respectively. In addition to the stop at the Schenker terminal, the truck performs loading and unloading rounds in the city of Terminal B1 and Terminal B2, and the loading time ranges from 30 min to 4 hours. Route B is driven every weekday, and Table 7.4-7.5 illustrates the departure, arrival, and lead times.

Table 7.4: Lead times between Terminal B1 and Stop B.



Terminal B1→ Stop B				
Action	**Location**	**Start time**	**End time**	**Total time**
Start (parked)	T.B1	17:30	18:30	1:00
Driving	T.B1 → Stop B	18:30	22:50	4:20
Exchange and break	Stop B	22:50	23:50	1:00
Driving	Stop B→ T.B1	23:50	4:10	4:20
End (parked)	T.B1	4:10	5:10	1:00

Table 7.5: Lead times between Terminal B2 and Stop B.



Terminal B2 → Stop B				
Action	**Location**	**Start time**	**End time**	**Total time**
Start (parked)	T.B2	18:30	19:30	1:00
Driving	T.B2→ Stop B	19:30	23:30	4:00
Exchange and break	Stop B	23:30	0:30	1:00
Driving	Stop B→ T.B2	0:30	4:30	4:00
End (parked)	T.B2	4:30	5:30	1:00

7.2.2 Charger sizing

Figure 7.5 demonstrates the energy consumption and charging of the truck operating on Route B, between Terminal B1 and Stop B. After completing the route from Terminal B1 to Stop B, the truck has 23 % battery remaining. It charges at Stop B for 45 minutes, and a charger with a power of 559 kW is required. When it returns to Terminal B1, 8% of battery is remaining, and to fully charge the truck during 1 hour at Terminal B1, a charger with the power of 620 kW is required. The charger sizes for Route B, from Terminal B1 to Stop B, are summarized in Table 7.6.

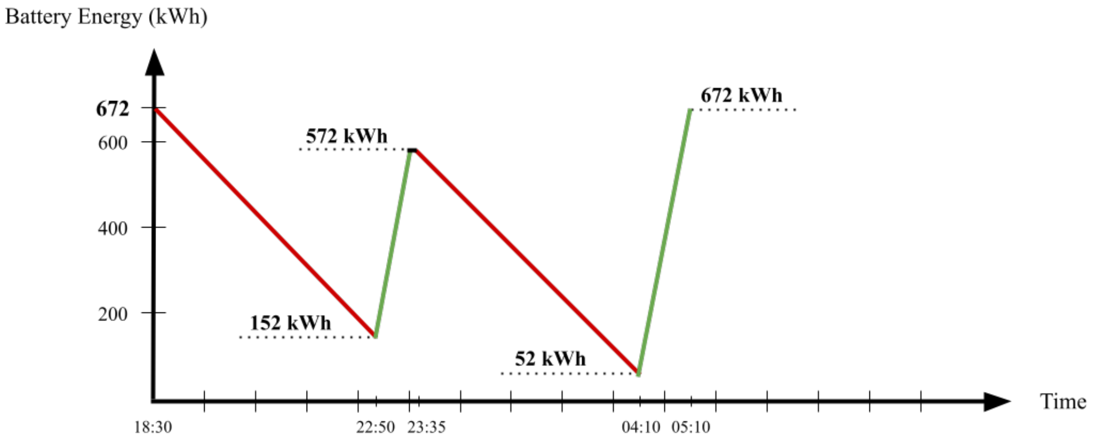
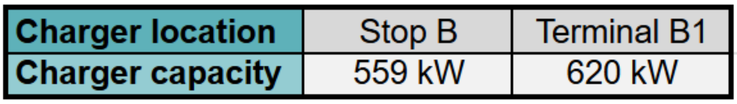


Figure 7.5: Energy balance diagram illustrating energy consumption and charging for Route B, Terminal B1 - Stop B.

Table 7.6: Summary of the charger sizes for Route B, Terminal B1 - Stop B.



Charger location	Stop B	Terminal B1
Charger capacity	559 kW	620 kW

Figure 7.6 demonstrates the energy consumption and charging of the truck operating on Route B, between Terminal B2 and Stop B. After completing the route from Terminal B2 to Stop B, the truck has 25 % battery remaining. It charges at Stop B for 45 minutes, and a charger with a power of 513 kW is required. When it returns to Terminal B2, 7% of battery is remaining, and to fully charge the truck for 1 hour in Terminal B2, a charger with the power of 622 kW is required. The charger sizes for Route B, from Terminal B2 to Stop B, are summarized in Table 7.7.

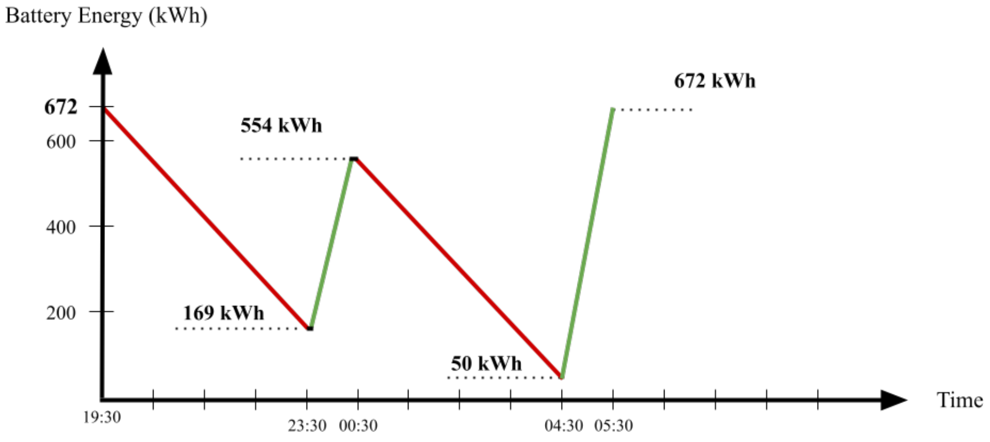
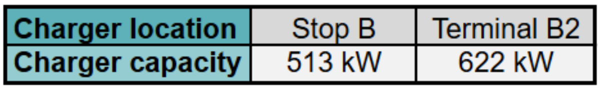


Figure 7.6: Energy balance diagram illustrating energy consumption and charging for Route B, Terminal B2 - Stop B.

Table 7.7: Summary of the charger sizes for Route B, Terminal B2 - Stop B.



Charger location	Stop B	Terminal B2
Charger capacity	513 kW	622 kW

The size of the charger at Stop B must be adapted to the highest capacity demand. Thus, the final charger size at Stop B must be 559 kW, adapted to the capacity demand for the truck from Terminal B1.

7.2.3 Total cost of ownership for Route B

When calculating the total cost of ownership for Route B with the current charger setup, the acquisition costs for the electric trucks are, once again, significantly higher than for the diesel trucks but the operational costs are lower. In Route B, minor waiting times of 15 minutes per truck occur at Stop B, due to the difference in arrival times at Stop B and the sequential charging, adding a small indirect cost component to the TCO calculation.

With only the two trucks utilizing the infrastructure, the TCO for the electric system is 9 837 180 kr more expensive than the diesel system. When an additional truck shares the infrastructure of three chargers, the loss is reduced to 4 007 230 kr. Further increasing utilization to four trucks utilizing the three chargers the electric system becomes is 1 936 288 kr less profitable than the diesel system. The results are illustrated in the graph below and the costs for these four scenarios are presented in Table 7.8 and Figure 7.7.

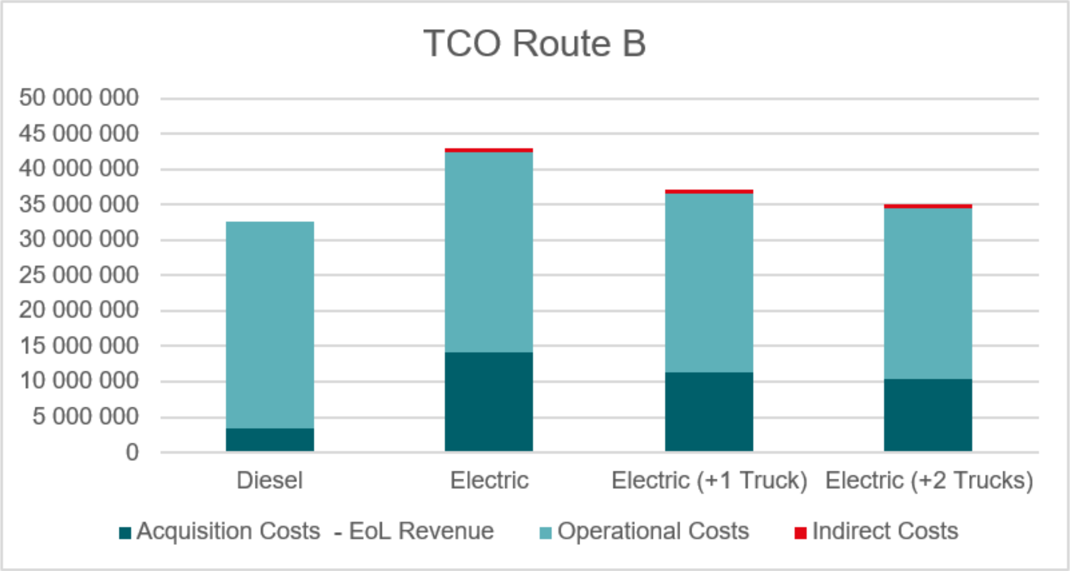
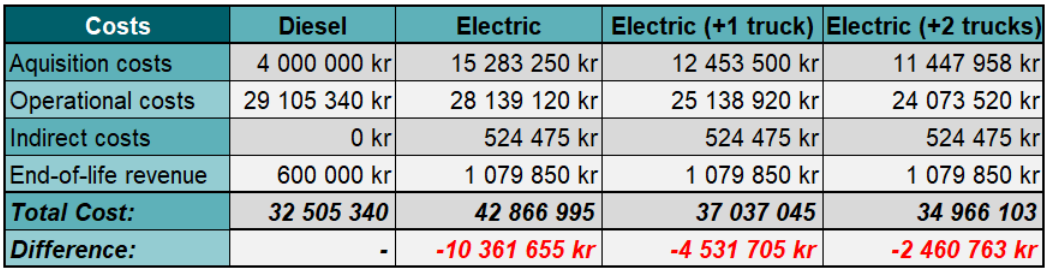


Figure 7.7: TCO for Route B Terminal B1-Terminal B2.

Table 7.8: Total cost of ownership for the diesel system contra electric system for Route B.



Costs	Diesel	Electric	Electric (+1 truck)	Electric (+2 trucks)
Aquisition costs	4 000 000 kr	15 283 250 kr	12 453 500 kr	11 447 958 kr
Operational costs	29 105 340 kr	28 139 120 kr	25 138 920 kr	24 073 520 kr
Indirect costs	0 kr	524 475 kr	524 475 kr	524 475 kr
End-of-life revenue	600 000 kr	1 079 850 kr	1 079 850 kr	1 079 850 kr
Total Cost:	***32 505 340***	***42 866 995***	***37 037 045***	***34 966 103***
Difference:	**-**	***-10 361 655 kr***	***-4 531 705 kr***	***-2 460 763 kr***

7.3 Case C

On Route C, the trucks operate between Terminal C1 (T.C1) and Terminal C2 (T.C2), and completes two trips per week, back and forth. To manage the current operational schedule two trucks will be needed, traveling opposite one another, due to the long lead time of this route. First, the route is not manageable with the initially stated battery capacity of 1050 kWh. However, with modifications including larger batteries and additional charging during the route, it becomes manageable. Thus, the required charger sizes at the terminals vary between 621-730 kW, with additional charges of varying sizes along the route. The TCO shows that when the route is operated with a larger battery, 1220 kWh, it is 0.5 MSEK less profitable with BETs and becomes profitable when 3-4 trucks are operating. Instead, with an additional charging stop in Stop C12, the route is 6.2 MSEK less profitable with BETs and becomes profitable when 3-4 trucks are operating Figure 7.8 shows a schematic illustration of Route C, and more details regarding them are outlined in subsections 7.3.1-7.3.7.

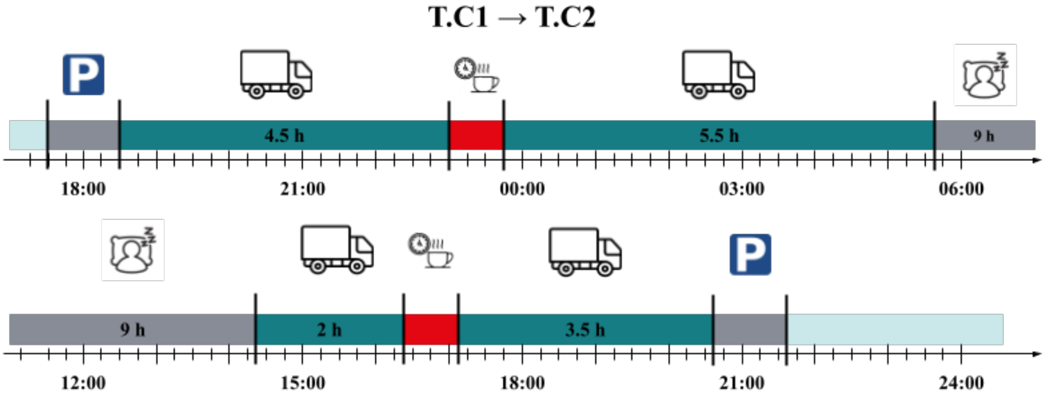


Figure 7.8: A schematic illustration of Route C, Terminal C1 - Terminal C2.

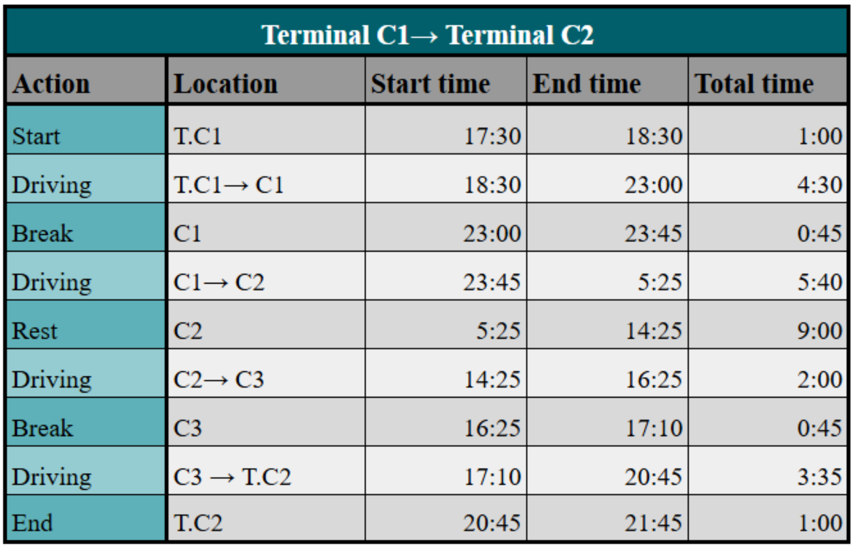
7.3.1 Description of route

The longest route of the studied routes is Route C, which goes between Terminal C1 and Terminal C2, and has a total distance of 1130 km one way. During the route, the truck makes a total of three stops for breaks; one 45 min break at Stop C1, one

9 hours rest at Stop C2, and lastly another 45 min break at Stop C3.

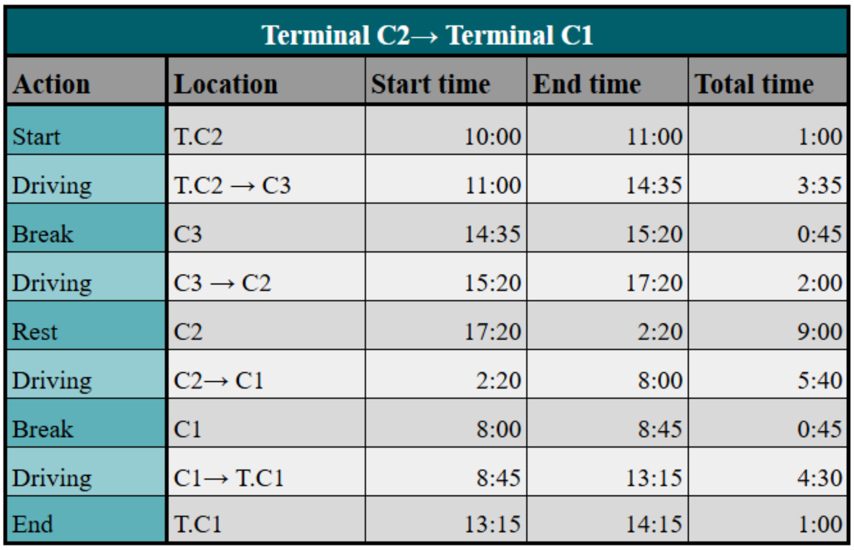
The truck departs from Terminal C1 twice a week, Tuesdays at 18:30, arriving at Terminal C2 on Wednesday 20:45, and again on Sundays arriving on Mondays, resulting in a lead time of 26 hours and 15 min. For the return route from Terminal C2 to Terminal C1, the truck also departs twice a week, Tuesdays at 11:00, arriving at Terminal C1 on Wednesdays at 13:15, and the same time on Thursdays, arriving in Terminal C1 on Fridays. The lead time is similar to the lead time from Terminal C1 to Terminal C2, totaling 26 hours and 15 min. Table 7.9-7.10 illustrates the departure, arrival, and lead times for Route C.

Table 7.9: Terminal C1 to Terminal C2 lead times.



Terminal C1→ Terminal C2				
Action	**Location**	**Start time**	**End time**	**Total time**
Start	T.C1	17:30	18:30	1:00
Driving	T.C1→ C1	18:30	23:00	4:30
Break	C1	23:00	23:45	0:45
Driving	C1→ C2	23:45	5:25	5:40
Rest	C2	5:25	14:25	9:00
Driving	C2→ C3	14:25	16:25	2:00
Break	C3	16:25	17:10	0:45
Driving	C3 → T.C2	17:10	20:45	3:35
End	T.C2	20:45	21:45	1:00

Table 7.10: Terminal C2 to Terminal C1 lead times.



Terminal C2→ Terminal C1				
Action	**Location**	**Start time**	**End time**	**Total time**
Start	T.C2	10:00	11:00	1:00
Driving	T.C2 → C3	11:00	14:35	3:35
Break	C3	14:35	15:20	0:45
Driving	C3 → C2	15:20	17:20	2:00
Rest	C2	17:20	2:20	9:00
Driving	C2→ C1	2:20	8:00	5:40
Break	C1	8:00	8:45	0:45
Driving	C1→ T.C1	8:45	13:15	4:30
End	T.C1	13:15	14:15	1:00

7.3.2 Charger sizing

Terminal C1 and Terminal C2. As is illustrated in the figure, the truck does not manage the sub-route between Stop C1 and Stop C2, since the required capacity for this sub-route exceeds the available capacity of 672 kWh. This problem can be addressed by either having a larger battery or making an additional stop for charging along the way. These examples are outlined in the following subsections.

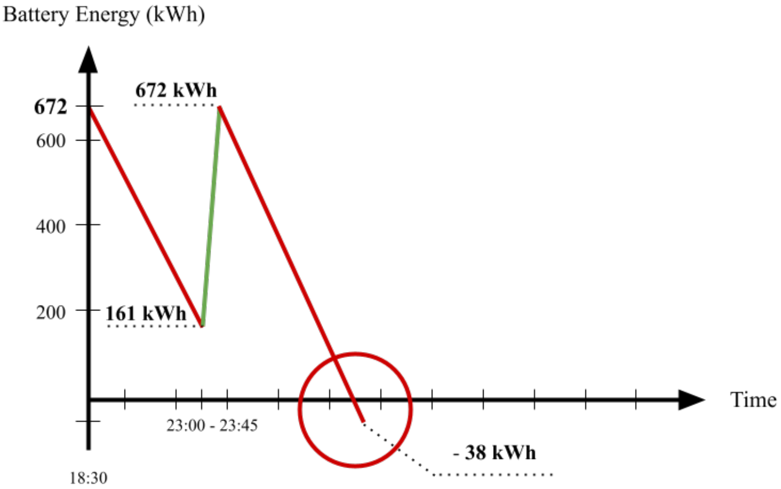


Figure 7.9: Energy balance diagram illustrating energy consumption and charging for Route C, Terminal C1 to Terminal C2.

7.3.3 Charger sizing (with a larger battery)

Figure 7.10 illustrates the energy consumption and charging of the truck on Route C, from Terminal C1 to Terminal C2, with a battery size adapted to the route specific needs. This results in a battery size of 1220 kWh, i.e., EoL capacity of 781 kWh.

When arriving at Stop C1, the truck has 34%, and charging during the 45-minute break, a charger with the power of 682 kW is required. When arriving at Stop C2, 9% remains, and the truck charges fully over 9 hours, and a charger with a power of 79 kW is required.

The truck then departs from Stop C2 with a full battery, and after reaching Stop C3, 68% battery remains, which is sufficient to manage the final subroute to Terminal C2 without charging in Stop C3. Arriving in Terminal C2, 11% battery is remaining, and for the truck to charge fully during 1 hour, a 693 kW charger is required. The charger sizes for Route C, from Terminal C1 to Terminal C2, with an adapted battery size, are summarized in Table 7.11.

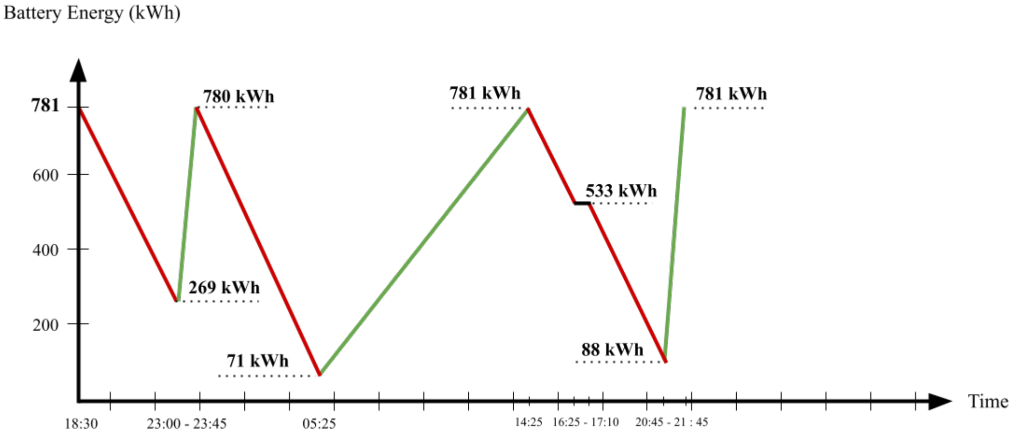
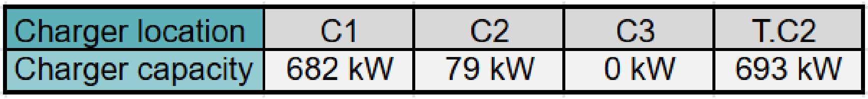


Figure 7.10: Energy balance diagram illustrating energy consumption and charging for Route C, Terminal C1 to Terminal C2, with a 781 kWh battery.

Table 7.11: Summary of the charger sizes for Route C, Terminal C1 to Terminal C2, with an adapted battery size.



Charger location	C1	C2	C3	T.C2
Charger capacity	682 kW	79 kW	0 kW	693 kW

Figure 7.11 illustrates the energy consumption and charging of the truck on Route C, back to Terminal C1 from Terminal C2. The battery size adapted to the route specific needs, as aforementioned.

When arriving at Stop C3, the truck has 43% battery remaining and no charging is needed to complete the following subroute to Stop C2. When arriving at Stop C2, 11% remains, and the truck charges fully over 9 hours, and a charger with a power of 77 kW is required.

The truck then departs from Stop C2 with a full battery, and when reaching Stop C1, 9% is remaining. Charging at Stop C1 for 45 minutes requires a charger with a power of 655 kW. Lastly, when arriving in Terminal C1, the truck has 7 % battery remaining, and to charge fully during 1 hour, a charger with the power of 730 kW is required. The charger sizes for Route C, from Terminal C2 to Terminal C1, with an adapted battery size, are summarized in Table 7.12.

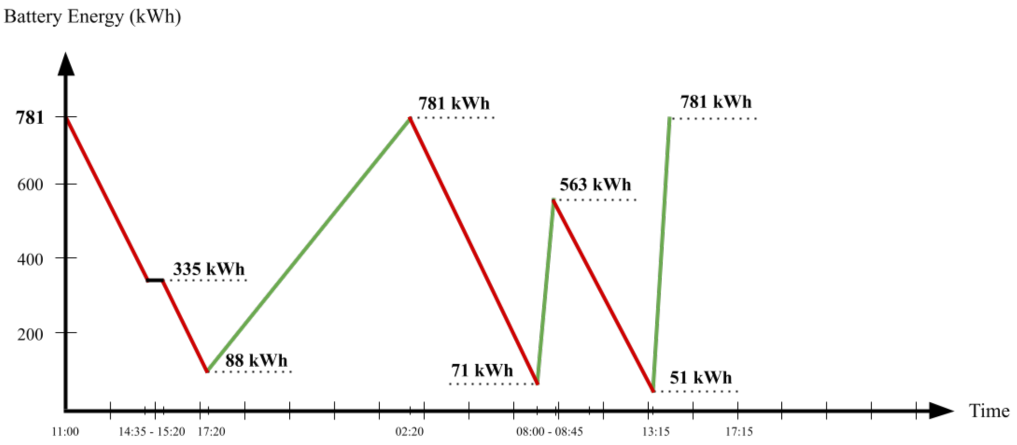
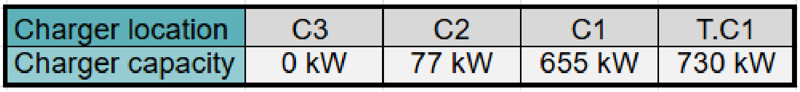


Figure 7.11: Energy balance diagram illustrating energy consumption and charging for Route C, Terminal C2 to Terminal C1, with a 781 kWh battery.

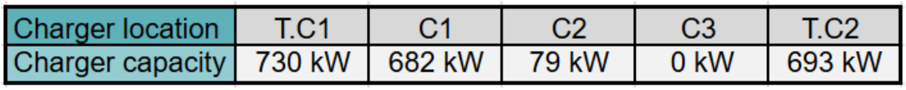
Table 7.12: Summary of the charger sizes for Route C, Terminal C2 to Terminal C1, with an adapted battery size.



Charger location	C3	C2	C1	T.C1
Charger capacity	0 kW	77 kW	655 kW	730 kW

The size of the chargers along the route must be adapted to the highest capacity demand at each charging location. Thus, considering the capacity demand from Terminal C1 to Terminal C2 and back to Terminal C1, as described above, the final charger sizes for a larger battery, and accommodating both directions are illustrated in Table 7.13.

Table 7.13: Summary of the required charger sizes for Route C, with an adapted battery size.



Charger location	T.C1	C1	C2	C3	T.C2
Charger capacity	730 kW	682 kW	79 kW	0 kW	693 kW

7.3.4 Charger sizing (with an extra charging stop)

Figure 7.12 illustrates the energy consumption and charging of the truck on Route C, from Terminal C1 to Terminal C2, with an additional stop for charging the battery. This additional stop is required for the truck to manage the route with a nominal battery capacity of 1050 kWh, i.e., EoL capacity of 672 kWh, and takes place at Stop C12, located between Stop C1 and Stop C2.

When arriving at Stop C1, the truck has 24% battery, and the truck charges here with a 197 kW charger for 45 minutes. At the additional Stop C12, the truck arrives with 9 % remaining in the battery, and it charges here for 30 minutes and requires a charger with the power of 650 kW. When arriving at Stop C2, 5% remains, and the truck charges fully over 9 hours, and a charger with a power of 71 kW is required.

The truck then departs from Stop C2 with a full battery, and after reaching Stop C3, 63% of the battery remains, and the truck charges here for 45 minutes with an 87 kW charger. The truck arrives in Terminal C2 with 7% battery, and for it to fully charge during 1 hour, a charger with a power of 627 kW is required. The charger sizes for Route C, from Terminal C1 to Terminal C2, with an additional stop at Stop C12, are summarized in Table 7.14.

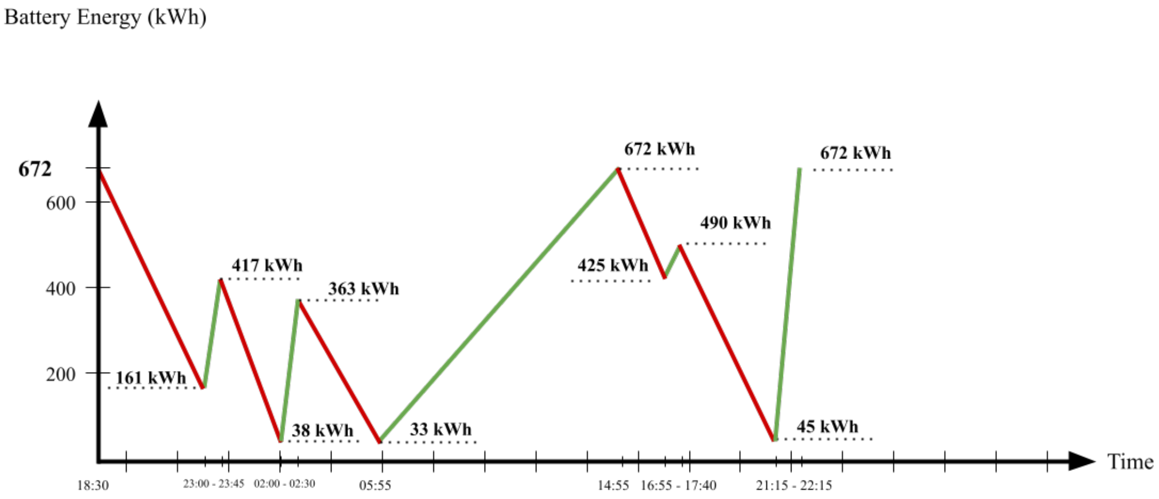


Figure 7.12: Energy balance diagram illustrating energy consumption and charging for Route C, Terminal C1 to Terminal C2, with an additional stop for charging in Stop C12.

Table 7.14: Summary of the charger sizes for Route C, Terminal C1 to Terminal C2, with an additional stop for charging in Stop C12.

Charger location	C1	C12	C2	C3	T.C2
Charger capacity	197 kW	650 kW	71 kW	87 kW	627 kW

Figure 7.13 illustrates the energy consumption and charging of the truck on Route C, from back to Terminal C1, from Terminal C2, with an additional stop for charging in Stop C12.

When arriving at Stop C3, the truck has 34%, and the truck requires a 61 kW charger for 45 minutes. When arriving in Stop C2, 4% remains, and the truck charges fully over 9 hours, and a charger with a power of 72 kW is required. At the additional stop at Stop C12, the truck arrives with 51 % remaining in the battery, and it charges here for 30 minutes and requires a charger with the power of 151 kW.

The truck arrives at Stop C1 with 6% battery, and when charging here for 45 minutes, a charger with the power of 700 kW is required to manage the last subroute. Upon arrival at Terminal C1, the truck has 8% battery remaining, and to fully charge the battery during 1 hour, a charger with a power of 621kW is required. The charger sizes for Route C, from Terminal C2 to Terminal C1, with an additional stop at Stop C12, are summarized in Table 7.15.

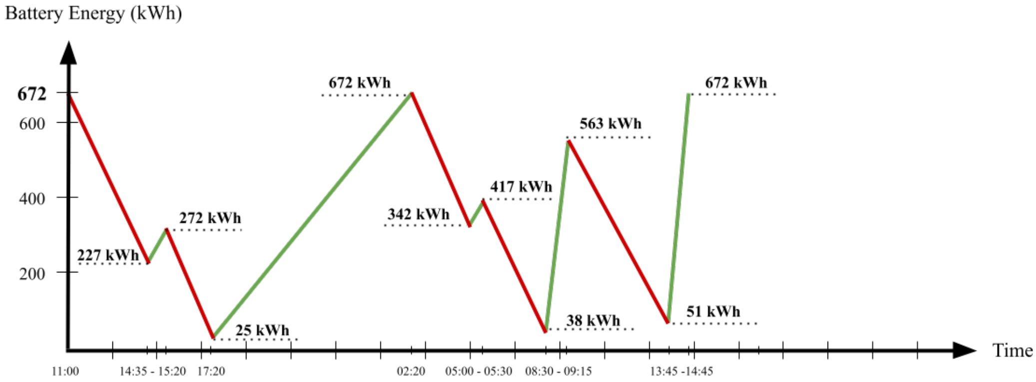


Figure 7.13: Energy balance diagram illustrating energy consumption and charging for Route C, Terminal C2 to Terminal C1, with an additional stop for charging in Stop C12.

Table 7.15: Summary of the charger sizes for Route C, Terminal C2 to Terminal C1, with an additional stop for charging in Stop C12.

Charger location	C3	C2	C12	C1	T.C1
Charger capacity	61 kW	72 kW	151 kW	700 kW	621 kW

Considering the capacity demand from Terminal C1to Terminal C2 and back to Terminal C1, as described above, the final charger sizes with an additional stop for charging at Stop C12, and accommodating both directions are illustrated in Table 7.16.

Table 7.16: Summary of the required charger sizes for Route C, with an additional stop for charging in Stop C12.

Charger location	T.C1	C1	C12	C2	C3	T.C2
Charger capacity	621 kW	700 kW	650 kW	72 kW	87 kW	627 kW

7.3.5 TCO for Route C (with a larger battery)

Route C is the longest and most energy-demanding route, requiring either extra charging or an extra large battery. The TCO when calculating with an extra large battery with a capacity of 1220 kWh results in a TCO 478 535 kr less profitable than the diesel system. The acquisition costs are almost three times as large, but the operational costs are reduced by half. When an additional truck splits the cost of the charging infrastructure the electric system becomes profitable with 2 362 848 kr. However, the charger at Stop C2 is not split by any additional trucks, due to the long charging time. Adding an additional, fourth, truck to share the charging infrastructure improves the profit further to 3 783 540 kr. The result is illustrated in the graph below and the exact costs for these four scenarios are presented in Table 7.17 and Figure 7.14.

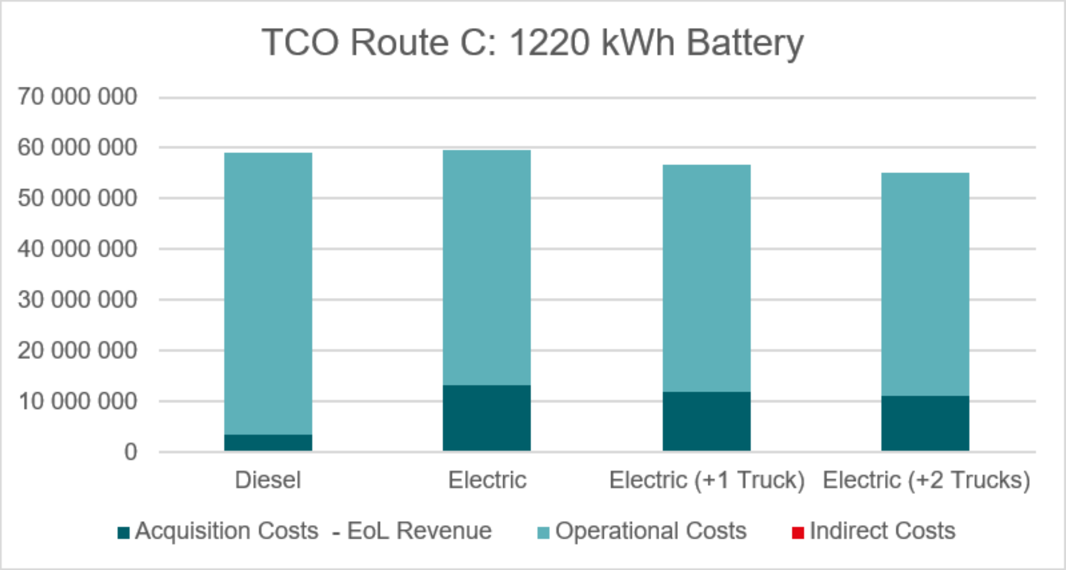


Figure 7.14: TCO for Route C Terminal C1-Terminal C2 with a larger battery capacity.

Table 7.17: Total cost of ownership for Route C with an extra large battery (1220 kWh).

Costs	Diesel	Electric	Electric (+1 truck)	Electric (+2 trucks)
Aquisition costs	4 000 000 kr	14 426 000 kr	13 057 417 kr	12 373 125 kr
Operational costs	55 614 480 kr	46 228 940 kr	44 756 140 kr	44 019 740 kr
Indirect costs	0 kr	0 kr	0 kr	0 kr
End-of-life revenue	600 000 kr	1 161 925 kr	1 161 925 kr	1 161 925 kr
Total Cost:	***59 014 480***	***59 493 015***	***56 651 632***	***55 230 940***
Difference:	**-**	***-478 535 kr***	***+2 362 848 kr***	***+3 783 540 kr***

7.3.6 TCO for Route C (with an extra charging stop)

The TCO when calculating with an extra 30 minute charging stop in Stop C12 results in a TCO 6 217 752 kr less profitable than the diesel system. When an additional truck splits the cost of the charging infrastructure the loss decreases to 505 630 kr and becomes profitable with 1 624 259 kr when a fourth truck is introduced. The extra charging in Stop C12 results in indirect costs of roughly 1 000 000 kr. The result is illustrated in the graph below and the costs for these four scenarios are presented in Table 7.18 and Figure 7.15.

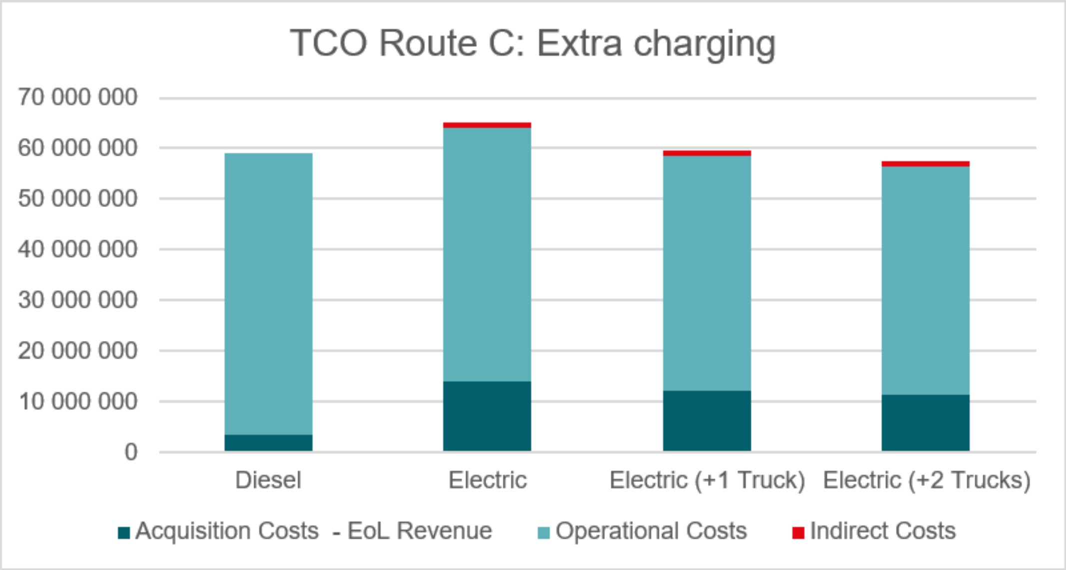
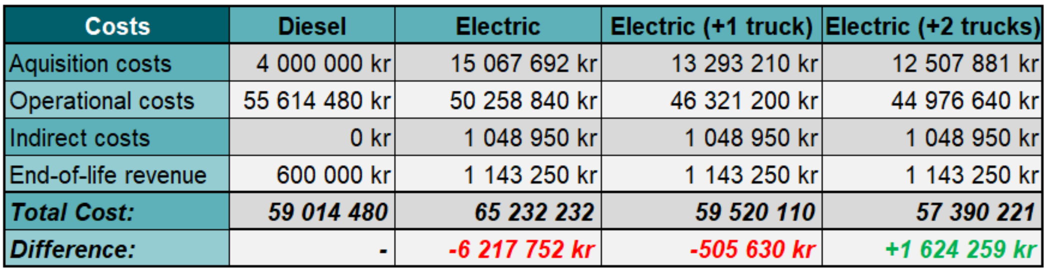


Figure 7.15: TCO for Route C Terminal C1-Terminal C2 with extra charging.

Table 7.18: Total cost of ownership for Route C with an extra charge stop in Stop C12.



Costs	Diesel	Electric	Electric (+1 truck)	Electric (+2 trucks)
Aquisition costs	4 000 000 kr	15 067 692 kr	13 293 210 kr	12 507 881 kr
Operational costs	55 614 480 kr	50 258 840 kr	46 321 200 kr	44 976 640 kr
Indirect costs	0 kr	1 048 950 kr	1 048 950 kr	1 048 950 kr
End-of-life revenue	600 000 kr	1 143 250 kr	1 143 250 kr	1 143 250 kr
Total Cost:	***59 014 480***	***65 232 232***	***59 520 110***	***57 390 221***
Difference:	**-**	***-6 217 752 kr***	***-505 630 kr***	***+1 624 259 kr***

8

Empirical findings

This chapter presents the empirical findings derived from interviews with various key actors within Sweden's transportation system. The aim of the interviews is to provide insights into each actor's perspectives associated with the transition towards BETs. These insights are structured around three main areas: the future roles and relationships of the actors, the challenges with introducing BETS, and the requirements and enablers for a successful transition.

The eleven actors interviewed are split into three groups: the haulers, the OEMs, and the supporting actors. The haulers include the three haulers that perform the transportation activities of the case routes described in chapter 7 as well as DB Schenker's internal hauler company and a hauler that is at the forefront of the transition. The OEMs are the companies that support the haulers and LSPs with two key resources: the BETs and the chargers. The supporting actors are the actors that are key in supporting the transition: an energy provider, a CPO, and a research and innovation facilitator.

8.1 Haulers

The following section presents the insights from the five hauler companies interviewed. Firstly, Hauler A is the hauler company operating Route A, Hauler B is the hauler operating Route B, and Hauler C operates Route C. Furthermore, the pioneers Falkenklevs Åkeri, who have electrified 95 % of their transportation fleet. Finally, DB Schenker Åkeri is the subsidiary of DB Schenker that handles 25% of its truck transportation assignments.

8.1.1 Hauler A

Hauler A is a hauler company that owns and operates a fleet of roughly 35 trucks, and they transport goods in DB Schenker's network, such as Route A. They aim to contribute to a more sustainable future by offering and developing efficient transportation services, offering transportation according to the Fair Transport standard. Their fleet consists mainly of diesel trucks, and they recently invested in gas-fueled trucks that they use by request from a specific customer. They also offer the option to use HVO if customers want a more sustainably friendly option. No investments have been made in BETs since they don't find these economically viable for their longer routes. On their short route of Route A they utilize older trucks, that are already fully depreciated, and that have already driven roughly 80 000 - 90 000 miles for other transportation tasks. These older trucks are more susceptible to breakdowns or other issues, which are more easily resolved on the shorter routes, and it is the reason behind the usage of these trucks on the shorter routes. Hauler A is skeptical of the sustainability of battery production and views gas-fueled trucks more favorably.

Hauler A explains that cooperation between haulers was more common ten years ago, and stricter regulations along with tight delivery schedules have made the collaboration more difficult.

> *"In the past, maybe ten years ago, it could happen that I had a truck, someone else had a trailer, and we were going to the same place. We would say: 'I'll take your trailer, I'm going that way anyway.' But today, the regulations and time constraints are so strict that it doesn't work anymore."*

A transformation to BETs would entail even tighter schedules, and decreased flexibility due to the dedicated routes and the planned charging along the way. They also express skepticism towards collaboration, e.g., with shared charging infrastructure, and favor independent solutions, such as owning charging infrastructure and having solar panels to secure energy at a favorable cost. They convey doubt about relying on public charging due to the high prices, and the fluctuations and unpredictability.

Hauler A outlines several challenges with the transformation to an electric transportation fleet. Firstly, Hauler A mentions the cost of public charging, and that it is too expensive for BETs to be a viable option instead of diesel trucks. The cost of charging is unpredictable and associated with volatility, making long-term planning more difficult. This transformation is also characterized by high investment costs, and Hauler A mentions that although subsidies partly relieve the financial burden, the required investment in both BETs and charging infrastructure is still too high.

Regarding the batteries, Hauler A mentions that the capacity of them is not sufficient for routes up to 450-600 km. These routes would then require a stop for charging along the way, which is, according Hauler A, not possible due to the tight schedules. These thigh schedules and lack of operational flexibility make it difficult to fit in time for charging. This reduction of flexibility is also something that Hauler A believes slows down the adoption of BETs.

Additionally, according to Hauler A, there is a lack of charging infrastructure for the transformation to be possible. They specifically mention chargers at terminals, which they believe are vital for the transition, for trucks to be able to charge while loading and unloading. Lastly, Hauler A points out misalignment with current operational models as another challenge for the transition, i.e., that Hauler A is utilizing old trucks which are written-off, for short routes, as for example the studied Route A.

Hauler A sees multiple requirements that must be met for a successful and widespread transformation to BETs in the transportation system. Firstly, they point out that the charging infrastructure must be developed, with an emphasis on it being both reliable and affordable. This is also because electricity prices must be predictable and reasonable, and according to Hauler A, solar panels at terminals could act as an enabler for cheaper and predictable electricity cost. However, since solar panels generate power during the day when the trucks are operating, there is a need to save and allocate the energy when needed, e.g., during the night.

Moreover, Hauler A mentions requirements in terms of increased rigidity of the operations and planning, due to the lack of flexibility. The BETs need to have dedicated routes and sufficient capacity to manage the routes, without the need for charging along the way. Another requirement that Hauler A brings up is the importance of clear coordination and commitment from other stakeholders in the transportation system, such as Schenker. By this, they mean a clear long-term strategy for the green transformation.

Lastly, Hauler A brings up the importance of financial support for the initial investment in BETs and the associated charging infrastructure. This is because these investments are significantly higher compared to the investment associated with diesel trucks, and hauler companies, in turn, operate with small margins, making these investments entail an increased commercial risk.

8.1.2 Hauler B

Hauler B is based in the city of Terminal B1 and they mainly offer distribution services in southern Sweden, but they also have some longer routes that they offer transportation services for, such as the line-haul route between Terminal B1 and Terminal B2. Approximately 90% of the goods transported by Hauler B is for DB Schenker. The company has invested in two battery electric parcel vans that have package delivery assignments in the port of the city of Terminal B1, but no investments have been made in larger BETs. Their current fleet is relatively new and Hauler B made a large investment in this new fleet right before the recent improvements in BET range, explaining why there are no current BETs in their fleet. The company does, however, see the possibilities of introducing BETs in the future and mainly in their distribution operations. When asked about the possibility to electrify longer routes, like Route B, their response was:

> *"When it comes to Route B specifically; it's not something we have looked into at all. Right now, it feels far off, how would you even operate a truck that drives between Terminal B1 and Terminal B2 at night, then also performs assignments in the city of Terminal B2 during the day before returning to Terminal B1 again? It's not like the truck that goes between*

> *Terminal B1 and Terminal B2 stops at Terminal B2 for the afternoon before heading back down to Terminal B1. Electrification still feels like it's a few years away from being able to handle these assignments. Furthermore, we have departure and arrival times to consider; how long does charging take? When do the drivers take their breaks, and where can we fit them in? There are many parameters that need to be adjusted when introducing electric trucks."*

Hauler B has a good relationship and an exchange of knowledge with other Haulers, when it comes to knowledge regarding HVO driven trucks. The transition to HVO trucks is not something Hauler B has made yet, however, there is an interest. The knowledge exchange includes how haulers that have implemented HVO trucks perform their TCO calculations, etc. Hauler B describes these discussions as active and thoughtful. Furthermore, Hauler B also has a collaboration with Volvo, where Hauler B is offered to try new HVO trucks and BETs.

Regarding the future relationship with Cirkel K and OKQ8, Hauler B believes that it will be similar to the relationship they have today, e.g., dialogue regarding how much they are predicting to consume, and negotiation of the price accordingly.

The barriers Hauler B see for the transition are the driving time, the capacity of the battery, meaning that the truck may not manage to complete the route, and weight limits. However, Hauler B expresses that they see the cost for the BET as the biggest operational challenge, and they have not investigated what the operational cost will be, for example the cost for public charging along the way.

Furthermore, Hauler B also expresses uncertainty regarding the flexibility, as BETs may take longer time to perform a route compared with a diesel truck. Which may result in the transportation taking longer time. That does not go in line with the fact that people expect to receive their packages quickly, only 1-2 days. This means that departure and arrival times must be reviewed, which is another modification required by the haulers.

According to Hauler B, range and capacity of the batteries are limiting factors, and therefore, further development of the batteries is necessary in order for the longer routes to be manageable. Another key aspect they mention is the need for enhanced charging infrastructure. For example, they describe that there are only two charging points near Terminal B1, which is insufficient if the adoption of BETs becomes more widespread.

Fixed operation points, e.g., as the trailer swap at Stop B, must align with the need for charging. In general, Hauler B believes that the charging requires coordination with rest times, and alignment with the general delivery schedule. Another aspect mentioned by Hauler B is the timing of the replacement of an old diesel vehicle fleet. This must be aligned with the life cycles of the trucks and their depreciation, and Hauler B explains that they had recently invested in a new diesel fleet when BETs became a viable option, thereby delaying their potential transition.

Hauler B emphasizes collaboration, and expresses that haulers alone are not capable of making this transition, and that it is rather a system change that is required. Investment and initiative from other actors such as OEMs, energy providers and logistics companies are needed. This also includes engagement by terminals, by providing charging infrastructure at their facilities.

Additionally, Hauler B also sees requirements from the customer purchasing the logistics services, and their willingness to pay extra for sustainable transportation. Hauler B believes that the demand for BETs is still low, and that customers choose HVO as an alternative after comparing the cost for BETs in relation to HVO trucks. Lastly, considering the customers, Hauler B also believes that there must be some behavioral and expectation changes from the customer's point of view, i.e., accepting slower deliveries compared to today´s, which BETs may imply.

8.1.3 Hauler C

Hauler C carries out transportation tasks for multiple clients, with DB Schenker being their largest customer. It is the fourth generation of a family business, and it has carried out the task of Route C for roughly five years for DB Schenker. Their fleet mainly consists of diesel trucks, but they have invested in a couple of BETs this year, which they have found most suitable for tasks below 20 miles and where there is an opportunity for a few hours of charging time. They invested in these trucks to learn more about the challenges and opportunities with BETs. Furthermore, they believe that BETs can be both an economical and sustainable option for trucks that carry out assignments that total roughly 40 to 50 miles driven per day. Hauler C states that economic viability is the most important factor to consider when implementing BETs; stating that the decision making of introducing BETs on routes would be simple if they outperform diesel trucks economically.

According to Hauler C, collaboration and cooperation between actors are necessary for the transition to BETs to make the transition economically viable. Not as it is now, where charging infrastructure providers are focusing on maximizing their profits, leading to expensive prices for electricity. This does not facilitate the transition, but rather the opposite.

Furthermore, Hauler C emphasizes cooperation within the transportation network, e.g., that logistic service providers offer charging at their facilities, so the truck can charge while loading and unloading. This must be at reasonable prices to stimulate and not prevent. Eggen Åkeri also mentions shared services such as solar energy pooling as a part of the solution. In general, it is a broader responsibility, and the haulers cannot carry this transition themselves, and the haulers need support from both the network and policy makers.

The most prominent challenge according to Hauler C is the lack of charging infrastructure and mismatch between charging needs and stops for breaks, consequently making planning difficult, especially for longer routes like Route C. In general, making sure the truck has an adequate battery level to manage the route. Another challenge mentioned is the high dependency on having a fully charged battery, for the truck to manage the route, without unplanned stops for charging. These unplanned stops for charging interrupt the schedule, thus reducing the efficiency of the operation. Additionally, Hauler C mentions the loss of flexibility, compared with diesel trucks. Due to the aforementioned factors, they believe that the longer distances, such as Route C, are far away from being suitable for BETs.

Hauler C expresses that the burden of transitioning from diesel to electric trucks is being unfairly placed on those further out in the transportation chain, i.e., the haulers, which are companies associated with tight margins. These tight margins make it difficult for them to make additional heavy investments with a lot of uncertainty, which this transformation is associated with. This implies that Hauler C's decision is to wait with electrification of the transportation fleet.

"I do not want to risk the money we have earned."

According to Hauler C, a successful transition to electrified transportation imposes demand on long distances, good capacity of the battery, and high accessibility to charging infrastructure along the road. Then there is also the customer's view and behavior, regarding opening hours and conditions of the goods reception, highlighting great cooperation with the customers. Regarding the transportation network, Hauler C emphasizes charging and the importance that it coincides with the breaks and the required rest times. Furthermore, this transformation is a holistic solution, where infrastructure and the economic incentives play an important role. This includes requirements in terms of the price for charging, which must be economically viable, and creating more collaborative solutions, such as charging possibilities at terminals.

8.1.4 Falkenklev Logistik

Another hauler was interviewed, Falkenklev Logistik AB, who mainly delivers goods for DHL. Falkenklev was interviewed because they are at the forefront of electrification and may offer perspectives that differ from those of other haulers. The company is the third generation of a family business that recently started to focus on sustainability and electrification, due to their new management. They started in 2022 by building a solar power plant in southern Sweden, purchasing five electric vehicles, and creating a charging station. Their vision is having a green transportation chain where they produce their own energy, own the charging stations, and have 100% electric vehicles. They have continued by building more solar power plants, with the vision of them producing in total more energy than their trucks consume, on a yearly basis. Furthermore, their current fleet now consists of 95% electric vehicles, and they plan to replace the remaining 5% of diesel trucks next year, 2026. The fleet consists of roughly 15 large BETs and 40 battery electric parcel vans. When asked how long the large BETs usually drive, they answered:

> *"When we look at the first ones we got in 2022, they had the range to travel roughly 12-15 miles. The new trucks we will get from Scania will be able to go up to 35 miles, so things are really developing."*

Flakenklev believes that new services will emerge during transition to BETs, regarding electricity and charging, consequently leading to relationships with new actors. They also have a positive attitude towards shared charging infrastructure and want as many as possible to use their charging stations, to increase the utilization, thus decreasing the costs for them. Offering charging infrastructure will probably lead to some new relationships with those utilizing the charging. However, one previous relationship Falkenklev had, and which is now fading as part of their transformation, is their relationship with the CPOs. This goes in line with their objective of transforming to a 100 % electric transportation fleet supplied by energy from their own charging infrastructure.

Falkenklev explains that they see the cost for BETs as the biggest challenge, and that it accounts for 95% of the problems. The remaining 5% is flexibility and range, which they view as a minor problem. Their longest route is 350 km, which they manage without any notable issues with their current BETs. However, support charging with public infrastructure occurs occasionally during these routes, and they require a bigger battery to overcome this. Falkenklev also mentions the currently lower diesel prices as a barrier, which makes diesel trucks a more viable option at the moment. Furthermore, they emphasize the importance of the customers' willingness to pay extra for green transportation, and explain that DHL, which is a major and important customer, has contributed and offered additional compensation for green transportation.

Falkenklev has an extensive charging infrastructure, and the utilization of the chargers is highlighted as critically important, and is viewed as a barrier, with an ongoing effort and dedication of continuous improvement.

Falkenklev mentions the possibility of producing your own electricity, consequently leading to favorable electricity prices, as an enabler for the transition. Regarding requirements in the surrounding network on the other hand, Falkenklev mentions grid balancing with the help of batteries, and getting compensation financially by being standby to the grid. Also, new business models for battery storage, where aged batteries are utilized and thus increase their second-hand value.

8.1.5 DB Schenker Åkeri

Schenker Åkeri AB is the subsidiary hauler company of DB Schenker Nordics and it handles roughly 25% of DB Schenker's transportation assignments, with the other

75% being handled by multiple different and smaller hauler companies. The goals of Schenker Åkeri are aligned with the goals of DB Schenker, previously explained in section 1.1, and the goal is to have 100% electric parcel vans and 56% of distribution trucks by 2030. The efforts of introducing electric trucks in line-haul operations are currently limited to the E-Charge project where a BET drives between Jönköping and Södertälje, but they have introduced electric parcel vans in their distribution operation. Regarding the introduction of BETs in distribution and line-haul operation they state the following:

> *"From a TCO standpoint, we still can't make the numbers work for these trucks [distribution, 16–18 tons], and that's what's delaying electrification. Diesel is too cheap, and at the end of the day, customers just aren't willing to pay. In practice, we could make the switch, but if we went all in, we'd go bankrupt pretty fast. Everything around it needs to keep up. That's probably the biggest challenge when you're operating in a network; it's not enough for just one customer to be willing to pay. [...] Then we have the 26-ton trucks, like the E-Charge vehicle, but I don't see us electrifying those anytime soon. That's partly because there just aren't any [viable] products on the market, and partly because these trucks run double shifts."*

The transformation to BETs will lead to a greater need for coordination and collaboration between the business units within DB Schenker Nordics. For example, increased collaboration with Schenker Fastigheter, who owns and operates their terminals, due to the need for charging possibilities while the BET is loading and unloading.

Additionally, with this transformation comes new needs, including e.g., the need for charging, support and monitoring of the chargers, and payment solutions for the charging. In this initial stage, Schenker believes that these services will be provided by different actors, which entails new relationships with these actors. This also builds upon their beliefs in an increased need for coordination and collaboration in the transportation network, both with already existing and new actors.

In general, the pressure to perform the transformation to BETs is placed on the haulers and transportation companies, which comes with the need for large investments in charging infrastructure and the BETs. However, many of these companies are small, and have difficulties making these investments themself, thus they need cooperation and support from other actors.

Schenker outlines several factors which they see as barriers for introducing BETs in the transportation system. The first factors concern the charging infrastructure, where they point out charging times and charger capacity, that BETs require long charging times, which are not compatible with operating times in the transportation system. Otherwise, it needs to be compensated by large chargers and thus large costs. There is also the challenge of reaching sufficient utilization of the chargers, and the risk of multiple BETs requiring charging at the same time and consequently creating a bottleneck in the system. Additionally, regarding the charging infrastructure, Schenker points out the lack of a well-functioning holistic solution, including hardware, software, support, and payment.

Regarding the economic factors for BETs, Schenker sees the high initial investment of BETs, compared with diesel trucks, as a challenge. Especially a BET with a significantly large battery, which is a requirement for longer routes. According to Schenker, the lower operating cost during the BETs life cycle does not compensate for these higher investment costs of both the truck and the chargers.

Another challenge according to Schenker is that the current transportation system is adapted to diesel trucks, e.g., when it comes to time schedules for collection of goods and distribution. Electrified transportation requires a new structure of Schenker´s transportation operations, and Schenker sees challenges in adopting the current schedules accordingly. For example, two-shift operations yield very limited time to charge.

The battery capacity is an additional factor Schenker views as a challenge, limiting their transition to electrify the line haul operations. The lack of capacity results in the truck not managing the routes, without excessive charging along the way, and risks not managing to complete the route without depleting the battery.

Firstly, Schenker emphasizes the cost of charging, and that this must be offered at reasonable prices for the overall investment to be financially justifiable. Due to the higher upfront investment required for BETs compared with diesel trucks, the operational costs savings must be significantly greater to ensure return on investment, which Schenker currently finds challenging. Furthermore, Schenker mentions the development of the charging infrastructure as a requirement for the transition, where the aim should be to have high availability of reliable chargers, and with high effect.

Another requirement according to Schenker is holistic solutions in the transportation network, which they currently see as missing. By this, they refer to an actor that offers a complete solution, e.g., charger, support, monitoring, payment solution, and service of the chargers. Schenker Åkeri is one of the largest hauler companies in Sweden, and they express that a transformation for them is much more complex compared with a smaller hauler company. Therefore, they believe that it may be more suitable for other actors to take the first step in the transformation towards BETs.

8.2 BET & Charger OEMs

The following section presents the insights from the three manufacturing companies, Volvo, Scania and ABB. Truck manufacturers Volvo and Scania are working actively towards the electrification of trucks and are involved in collaboration projects such as E-Charge and REEL. The charger-manufacturer ABB, focuses on the development and production of charging infrastructure technology, and has been working with EV technologies for over a decade.

8.2.1 Volvo AB

Volvo AB produces and develops heavy-duty vehicles and consequently the company is an important actor in the network when it comes to the transition towards electrification of the transportation system. As an OEM they are responsible for the development and production of the trucks that the rest of the system relies on. Volvo is engaged in electrification and participates in collaborative projects such as E-Charge and REEL to support this transition, by helping further develop their trucks while also allowing them to display the possibilities of the trucks. The focus of Volvo is currently on BETs but they are also developing other types of trucks, such as fuel cell hydrogen based ICETs. Furthermore, Volvo has established the company Volvo Energy to support their transition from diesel based ICETs to BETs. Volvo Energy helps by offering charging solutions and in the future the company aims to repurpose used up batteries and give them a second life, hoping to improve the residual value of the batteries. This could improve the TCO during the battery's first life, making BETs more attractive to customers.

Alongside BETs comes also the need for charging infrastructure, which means that Volvo's current relationship with charger manufacturers will further develop. Moreover, financing of BETs is a major question, since these are a larger investment for the customers compared with diesel trucks, meaning that relationships with companies offering financing will become even more important in the future.

Overall, Volvo sees collaboration among the actors involved in this transformation as a key factor for this to be successful, as well as good communication and dialogs between the actors. Such dialogs have worked well in the past, during the transition from diesel to gas. However, a difference then was that this occurred during a longer period, whereas Volvo aims for a much faster transition this time, hence they are willing to push from all angles to accelerate the process.

Furthermore, Volvo highlights the large differences in the progress of this transition between the European countries, both regarding the adaptation of BETs and the availability of charging infrastructure. Volvo believes that one reason Sweden has come so far in this transition is partly due to the cooperation between stakeholders e.g., through many large-scale joint projects. Thus, demonstrating how such initiatives can spur development.

Volvo does not anticipate any issues for the regional routes. For longer routes, however, Volvo mentions barriers such as the battery capacity and charging infrastructure, and particularly the absence of MCS chargers. Nevertheless, considering the phase of technical development, they believe that these barriers will soon be overcome.

Additionally, Volvo points out that for the transition to take off, consumers must see economic incentives in the switch to BETs, which include the cost of the truck and battery, and the cost for public charging. However, they emphasize that Sweden is in the forefront of the development of public charging infrastructure, considering CCS chargers. The availability of MCS chargers needs to be widespread, which Volvo believes will be soon.

Regarding the requirements for the transition to BETs, Volvo holds the view that the market needs to mature, and increase awareness about electrification, and to dare to take the step to try out BETs as a solution. Volvo mentions incentives from policy makers that spur the transition, as one among many methods. This can e.g. be made through tax reliefs for BETs during the transition phase, or financial support for the purchase of them, in the short run. Other stakeholders that must act in favor of the transition are e.g., the companies purchasing the transportation services and the terminals, by offering charging opportunities at their facilities. Apart from that, Volvo also explains that they may need to be prepared to pay a higher price for these transports, at least in the initial phase of the transition.

Furthermore, actors such as Trafikverket must be prepared for this transition and provide charging infrastructure, e.g., at rest areas along the way, and energy providers must be ready to provide electricity efficiently. Overall, there are many stakeholders that need to be aligned at work towards this common goal. Lastly Volvo notes that it is reasonable to review the weight limit for the trucks, as BETs are heavier due to the battery. This would help ensure that weight regulations do not become a limiting factor for the transition.

8.2.2 Scania

Another truck OEM, Scania CV AB, has focused its electrification efforts on heavy-duty trucks requiring larger batteries and longer operating ranges. In comparison, Volvo has more recently begun offering BETs with similar capabilities. Scania is also involved in multiple collaborative projects such as E-Charge and REEL. Scania is focusing on BETs for the near future while also developing other alternative types of trucks. Scania is aware that the transition to electric needs to be supported by green energy and that there are limitations to BETs currently. In Sweden there is a good supply of green energy making it a suitable location for the introduction of BETs, while other places in Europe might instead be better off by using gas-powered trucks from an environmental perspective. Similarly to Volvo, Scania has established their charging solution company Erinion to help support the transition towards BETs in the transportation system.

Scania highlights that the transformation of electrifying trucks entails new actors and relationships, particularly relationships associated with the charging infrastructure, such as the relationship between charge point operators and charger manufacturers like ABB. Another example is Scania´s subsidiary Erinion, which handles the installation of charger stations, whose emergence is a result of this transformation.

Besides these relationships, Scania sees that current actors in the system are adapting their business models to electrification, rather than new actors coming in and taking market shares, and gives OKQ8 and Circle K as examples, saying that these now offer charging infrastructure apart from their previous standard offer of fossil fuels and HVO. Furthermore, these relationships and collaboration are seen as crucial for this transformation, and that electrification is noted to open up for new business models through digitals tools, which in turn require interconnection and cooperation within the network of actors.

One uncertainty with BETs, acting as a barrier, is the lack of operating experience and data, which in turn makes it difficult to predict the need for maintenance, the second life value of the batteries, and the total cost of the life cycle of BETs. Scania also mentions challenges with the range of the BETs, and even though 80 % of the trucks in Sweden drive less than 300 kilometers per day, which is fully manageable with today's technology, there is still an inflexibility in some of the current business models, e.g., that Schenker´s line haul operation is optimized for diesel trucks, where loading and unloading, and refueling occur on different places and by different actors. This creates barriers, according to Scania.

Apart from a different structure of the transportation network required for electric trucks, compared with diesel trucks, Scania also sees challenges such as the high investment costs associated with BETs, which are a cost pushed to the haulers, who are, in many cases, small actors with already tight margins. Lastly, Scania mentions the lack of charging infrastructure as a challenge, affecting the planning and utilization of the trucks.

Scania states that changes must be made, and adapt the system to the BETs, rather than adapting the BETs to the already existing system which is adapted to diesel trucks. Furthermore, for a successful transformation, Scania also believes that requirements must be set towards the purchaser of truck services, e.g., through procurement policies that specify and demand electrical vehicles. Scania outlines that this is because today's system is structured such that it is the buyers that set the requirements, and not the haulers in the transportation system who switch their transportation fleet on their own initiative. Subsequently, this puts pressure on the customers, that they must be willing to pay extra for green transportation.

According to Scania, there are also requirements on the charging infrastructure, and considering the line haul traffic, it is a question regarding charging at strategically optimal places.

8.2.3 ABB

ABB is a technology company that plays a key supporting role in the electrification of the transportation system, through their development and production of charging infrastructure technology. ABB manufactures and services EV chargers for multiple applications, including cars, buses, as well as trucks. ABB has been working with EV charging technology for over a decade, initially the focus was on cars and buses but the focus on BETs has increased steadily. The type of chargers that ABB is currently offering are mainly CCS-chargers (up to 400 kW in power), but they are also developing MCS-chargers since they believe that these will become important in the future for heavy-duty vehicles.

ABB highlights that there will be more local service providers in the network to support the BET owners in terms of maintenance, monitoring and service of the trucks as well as the chargers. Stating that these actors could be key to quickly resolving issues, ensuring high uptime, and maintaining operational flexibility. Furthermore, ABB states that the transition towards an electrified transportation system would demand stronger collaboration between the technology providers like ABB with the other actors in the system like haulers, LSPs, CPOs, and energy providers to improve the knowledge exchange. Stating that the knowledge exchange is important for understanding each other's needs, constraints, and expectations of the technology and its usage. Furthermore, this early phase of infrastructure deployment will require dependable collaboration between different actors to ensure a reliable system for early adopters.

ABB highlights that the right charger must be at the right place, which can be a challenge since it must be coordinated with natural stops for the vehicles, in combination with where there is sufficient grid connection, which is not always the case. Additionally, ABB believes that there could be problems with obtaining sufficient energy in certain areas, and even "dark spots" where local grid limitations make it infeasible to install powerful chargers. Another challenge is that the application process for requesting grid connection can require considerable time.

There are also challenges with the electricity price, according to ABB, who mention that the electricity prices vary more between charging stations than diesel prices do. There could also be a greater difference between contracts for electricity prices compared with diesel prices. Lastly, ABB points out that low utilization of large chargers can make it hard to justify the investments in them.

ABB thinks that a key requirement for introducing BETs into the transportation system is to align charging with the current system set-up. The charging infrastructure needs to be expanded with chargers placed in locations that match the regulated rest periods of truck drivers. The charging experience needs to be seamless and predictable so that operators can rely on the system. ABB also believes that improvements in battery capacity and MCS charging will further support this operational reliability. This is essential because the transportation sector already relies on complex route planning and tight schedules. If the charging system is un-reliable, it only adds to the operational burden and risk for LSPs and haulers.

8.3 Supporting actors

The following section presents the insights from the three supporting companies interviewed. Circle K is a Swedish refueling provider that has adopted the role of a CPO in recent years. Vattenfall is the energy provider company that produces and provides the most energy in Sweden, it is also a grid provider but these businesses are split into two different subsidiaries. Finally, Lindholmen Science Park is a research and innovation facilitator that manages innovation projects that promote collaboration, horizontal collaboration, and knowledge exchange between the different actors in the transportation sector.

8.3.1 Circle K

Circle K is a refueling provider that has a nationwide network of fuel stations in Sweden and the company plays an important role in the transportation system by enabling long-distance freight transportation through the provision of fuels like diesel, HVO, and more recently also electric charging services for truck owners. Circle K aims to become a leading high-power charging infrastructure provider for BETs, and the company is currently building at a rate of roughly 300-400 charging points per year in Sweden. Not all of these are charging points with high power chargers, but the company is strategically prioritizing building these high-power chargers at high-demand areas and at existing sites where space and power access allow, focusing on transit routes and key logistics hubs for the truck transportation system. Circle K is also involved in projects such as E-Charge and E-Charge 2.

Circle K expects new energy actors providing electricity or gas to enter the market, meaning that traditional fuel providers like Circle K might lose some control of their current value chain. As a response they are looking at expanding their charging infrastructure and their opportunities for collaboration and investment in charging points together with larger logistics hubs, where they can reach high utilization of the chargers. In general, Circle K believes that there will be more cooperation and partnerships between different actors in the network during the development of charging infrastructure and BET technology. As an example, a manufacturing company like Volvo might contact Circle K to expand their charging infrastructure at a fuel station because a customer of Volvo requires charging opportunities if they were to purchase a BET.

The largest challenge Circle K faces in their transition of becoming a charging infrastructure provider, and a large challenge for the introduction of BETs is gaining access to the required grid connection and capacity. The lead time from applying for grid connection until a station is long, upwards of two to three years. Furthermore, Circle K might not be able to get the required capacity or a reasonable price that they can accept, which requires Circle K to replan their strategy regarding a specific station. Another challenge according to Circle K is the uptime of chargers and the available energy, since haulers and LSPs need reliable charging and charging times. Any delays for the haulers and LSPs are costly, hindering the transition towards BETs.

Circle K believes that there will be a change in their service offering in the future to match the requirements of their customers in terms of price and availability. A key requirement for this is to have many charging locations with bookable charging spots. The development of IT technologies supports the booking of chargers to increase charger utilization and lower the charging costs. The booking of chargers is something Circle K sees as a crucial requirement in the long term, but something that is less important in the short term when there are fewer users of the chargers. Furthermore, maintenance and software support are seen as requirements to ensure high up-time on the chargers so that haulers and LSPs can trust the charging system.

8.3.2 Vattenfall

Vattenfall is a major energy producer as well as a grid and charging infrastructure provider in Sweden, making the company's role important in the electrified transportation system. Consequently, Vattenfall plays an important role when electrifying the transportation system. The demand for electricity keeps increasing and many different sectors are electrifying their businesses, which requires large changes in the current electricity grid. Vattenfall participates in multiple projects like E-Charge and REEL to better understand the transport sector's challenges and together with other actors and academia find solutions to be able to accelerate the transition to electric vehicles.

Vattenfall believes that the electrification of the heavy transportation system will require stronger collaboration across industries in the future. One clear example is that the transport sector and energy sector have generally operated independently of each other historically. This separation of the sectors becomes blurred when introducing BETs, that are heavily reliant on grid connection and supply of energy. The actors in these sectors lack experience and knowledge of each other's industries, due to their independencies. Vattenfall has a deep knowledge of technical, regulatory, and safety requirements involved with large-scale electrical installation. Conversely, they know less about the operational constraints and business logic of logistics actors. New and closer relationships between the actors from the two sectors will therefore be necessary to bridge this knowledge gap. The future regulatory frameworks, safety standards, and system integration needs to be developed with input from multiple parties like OEMs, CPOs, LSPs, and haulers.

A challenge, in the short term, of electrifying road transportation from Vattenfall's perspective is being able to deliver the grid capacity required for the heavy-duty transport sector. Sufficient grid capacity is a challenge in certain geographical areas, e.g. in places along the larger road network. Another particularity for the heavy-duty transport sector, as opposed to passenger vehicles, are that they require significantly higher capacity in a specific time slot. Thus, there is little flexibility in the power demand from the heavy-duty transport sector, in location, capacity and time. Furthermore, making the BET owners susceptible to a large risk if there is not enough energy to charge the BETs and making it difficult to know the actual costs of switching to BETs. Related to this, the price of electricity contra the price of fossil fuels and how this is influenced by policymakers was also mentioned as a challenge for the introduction of BETs.

This is further problematized by the lengthy and unpredictable process of securing a grid connection, taking upwards of two years. This long lead time stems from a variety of factors. There can be high demand from customers requiring grid connections in certain locations and the prioritization system of first-in-first-out (FIFO) ultimately results in long waiting times. Furthermore the process itself is lengthy, requiring many steps such as investigating the available capacity and the needs of the customer, acquiring several permits from different authorities, as well as design, procurement and construction of the grid connection and potentially any other grid reinforcements required. The high demand and the long lead times also leads to customers applying for grid connections before having a clear understanding of their actual power demand or project timeline, simply to secure a place in the queue, resulting in longer queues.

Vattenfall considers several key requirements and enablers for the successful electrification of the transportation sector, as well as for the broader transition to a sustainable energy system. A central point is the need for strong political and regulatory support to reduce financial risks for energy producers and grid operators, and to incentivize sustainable investments.

One of the greatest short-term challenges is expanding the electrical grid at a pace that matches growing demand from sectors such as transport. Supporting the development of both grid capacity and charging infrastructure is essential to address the common “chicken-and-egg” dilemma where actors are hesitant to invest in BETs without sufficient charging options, while investments in infrastructure are delayed due to a lack of BETs in operation.

Digitalization and improved communication between energy producers and consumers were identified as crucial enablers. This is particularly important for balancing energy supply and demand as the system becomes more reliant on variable, less flexible renewable sources. Furthermore, with more actors generating and storing their own electricity, through technologies such as solar panels, BESS, or V2G, new coordination mechanisms are needed. These include more sophisticated data flows and tools for shifting or optimizing energy consumption patterns.

8.3.3 Lindholmen Science Park

Lindholmen Science Park is a company jointly owned by Chalmers University of Technology, the City of Gothenburg, and other business actors. It manages several key research and innovation projects such as E-Charge, E-Charge 2, and REEL. The company's primary role is to secure funding for research initiatives while also facilitating the involvement of a wide range of stakeholders and promoting knowledge-sharing and technological development within the transportation and mobility sector. As a neutral and independent actor, Lindholmen Science Park enables collaboration between multiple different companies, such as haulers, CPOs, LPSs, academic institutions, and truck manufacturers. These projects allow for horizontal collaboration, i.e. collaboration between companies that are typically considered as competitors, such as Scania and Volvo. By creating a shared platform for innovation, Lindholmen Science Park supports both the demonstration of new technologies and the expansion of applied research in sustainable transportation.

Lindholmen Science Park believes that the electrification of road transportation will introduce new actors into the system, such as actors providing solutions for integrating different management systems like fleet management, energy management, and booking systems. Furthermore, relationships between actors like LSPs, haulers, and Circle K will become closer and more structured. Lindholmen highlighted that having open and transparent relationships between the actors across the different sectors is important to support an effective transition towards BETs.

The first challenge Lindholmen Science Park highlights with introducing BETs is that the haulers who are expected to invest in BETs are constrained by low profit margins, making it necessary for BETs to be the superior option economically. Furthermore, larger investment costs require more financial strength to acquire good bank loans. The higher investment cost is further problematized by the current business set up between haulers and their customers, where short contracts create uncertainty for future income. This is especially important since it is the operational costs that are lower of BETs compared to ICETs, meaning that haulers need to exploit this benefit of BETs by having a high utilization of the trucks. The second challenge is the charging infrastructure and more specifically the issues with long lead times associated with establishing grid connections. The final challenge is that the cost of diesel is too low, which has been influenced and lowered by the policymakers in Sweden and that the current policymakers are not prioritizing electric freight transport.

Lindholmen Science Park believes that the main requirements for BETs are that they are cost effective and that they are reliable, since BETs cannot be adapted to the current system if they compromise delivery reliability. Furthermore, they state that line-haul applications are quite predictable, similarly to electric buses, and that it is not far from feasible to introduce BETs in line-haul operations with the current battery technology. An enabler to further improve the introduction of BETs in line-haul operations are improved batteries and other technologies such as electric trailers, where an extra battery is stored in the trailer, which can increase operational flexibility. Another enabler that improves operational flexibility is the development and deployment of MCS charging infrastructure. Lindholmen Science Park also thinks that development of IT-technologies such as booking systems, energy management, and fleet management are crucial for increasing utilization of chargers and improving the cost effectiveness of the system for all actors. Another enabler is a change in business structure, where haulers have longer contracts to allow them to recover their larger investments in BETs. Lindholmen Science Park states that there is no single solution for introducing BETs since the industry and the technological landscape changes rapidly.

8.4 Summary of empirical findings

Table 8.1 summarizes the empirical findings from this chapter, highlighting each actor's key insights in three areas: future roles and relationships, challenges in introducing BETs in line-haul operations, and the enablers and requirements for a successful transition.

Table 8.1: Summary of the empirical findings from the interviews.

Actor	Future Roles/Relationships	Challenges	Enablers/Requirements
Hauler A	Proposes an independent solution (own chargers, solar); less hauler-cooperation in future due to tighter schedules.	High cost and volatility of public charging, insufficient battery capacity, lack of terminal charging, high investment cost.	Affordable, reliable charging infrastructure; predictable energy prices; solar + storage; financial support.
Hauler C	Cooperation with LSPs for charging; haulers need more support in general.	Lack of infrastructure; misalignment of charging and rest breaks; high dependency on full charge; financial burden on haulers.	Long-range batteries; developed charging infrastructure; synchronized charging at stops; holistic collaboration.
Hauler B	Similar collaborations as they currently have, collaborations with OEMs to try new technologies.	Route feasibility (battery/range); investment risk; cost for public charging; less schedule flexibility.	Better batteries; improved terminal infrastructure; coordinated delivery & rest schedules; customer willingness to pay.
Falkenklev Logistik	Positive to shared infrastructure; offers own charging to others; believe new charging-related services will emerge.	95% of issues due to BET costs; diesel is cheaper; limited range only a problem occasionally.	Own energy production; battery storage; grid balancing; higher utilization of charging infrastructure.
DB Schenker Åkeri	Internal coordination is needed e.g., with terminals; new partners for support and charging services.	Long charging times; charger capacity/utilization; lack of holistic charging solution; high upfront costs.	Holistic solutions; affordable charging; high availability and fast charging; external actors may need to lead the way.

Volvo Group	Stronger roles for charger manufacturers; pushes for faster transition.	Imitation for long-route; lack of MCS chargers; economic incentives missing.	Policy support; charging at terminals/rest areas; change of weight limit; customer willingness to pay.
Scania	New business models and actor relationships (regarding charging); emphasizes collaboration among actors in the system.	Lack of BET experience/data; diesel-optimized system is inflexible; charging infrastructure gaps; burden on small haulers.	Adapt system to BETs; procurement requirements; strategically located infrastructure; customers willingness to pay.
ABB	Growth in local service/support providers; more cross-actor collaboration needed.	Right charger placement; grid constraints; long grid application times; low charger utilization.	Predictable charging; battery improvements; MCS support; well-placed infrastructure.
Circle K	Expects more collaboration; wants to co-invest.	Grid capacity access; long grid lead times; uptime and energy availability.	Developing charging infrastructure; booking system; high uptime; software and maintenance support.
Vattenfall	Closer integration coordination between energy and transportation sectors; shared regulatory and system input.	Grid capacity limitations; long connection processes; renewables’ inflexibility and misalignment of demand.	Political support; grid growth; digitalization for demand-supply balancing.
Lindholmen Science Park	Closer cross-sector ties and highlights openness/transparency.	Hauler margins too low; short contracts hinder investment; grid delays; low diesel cost.	Cost-effectiveness BET; better contracts; MCS infrastructure; booking systems for charging; reliable operations.

9

Analysis

This chapter presents the analysis and is divided into two main areas. The first area presents the analysis of the route cases in section 9.1, based on the results of chapter 7. This is followed by a sensitivity analysis of the TCO in section 9.2 where different critical factors are changed individually and analyzed in terms of impact on the TCO. Section 9.3 presents the scenario analysis where the impact on the TCO is analyzed when multiple factors are changed simultaneously for different future scenarios. The second area of the analysis is the analysis of the business network in section 9.4, which is based on the empirical findings of chapter 8.

9.1 Analysis of the case result

The results from chapter 7 shows that Route A and Route B are the two routes that are technically feasible to introduce BETs on, based on the given assumptions of a 1050 kWh battery, availability of MCS-chargers, and that the BETs should be able to fit into the current schedules. Due to the low charging times, MCS-chargers are needed for every route. For Route C it is not technically feasible to introduce BETs, but the results show that it would be more profitable to use a larger battery compared to introducing an extra charging stop.

Regarding profitability, it is evident that the utilization of the chargers has a big impact on the profitability. Furthermore, the utilization of the BETs also has a big impact on profitability, since Route C had the longest distance driven as well as the highest profitability. When distance driven increases it means that truck utilization is higher for the specific route. This explains why Route C is the most profitable of the studied cases, since the truck is pretty much only utilized for this route during the day. For Route A and Route B the trucks will be utilized for distribution rounds which are not accounted for in these TCO calculations, and if they were, this would increase the utilization of both the BETs and charger, thus improving the TCO outcome. Another important aspect to consider is that the results do not account for the cost of capital for each individual actor involved in each route. The required margins and capital costs associated with such large investments could potentially offset any savings from electrification, especially since the potential savings are non-existent or relatively small. Furthermore, the result of the TCO is highly dependent on the assumptions of the future and factors such as cost of diesel, cost of electricity, or cost of chargers and batteries. The sensitivity analysis and scenario analysis of the next chapters examine how changes in these factors impacts the TCO.

9.2 Sensitivity Analysis

This section presents a sensitivity analysis that examines how changes in key parameters such as cost of diesel, cost of electricity, cost of chargers, and residual values influence the outcome of the TCO-calculations. The analysis is based on the assumption that all other factors remain equal, except for the factor analyzed. Similar to the TCO results in Chapter 7, the analysis illustrates how the TCO is affected when two, three, and four BETs are charging the charging infrastructure. The sensitivity analysis examines these changes for Route B, since this route well represents a typical line-haul route with medium to long distances driven between terminals.

9.2.1 Diesel costs and electricity costs

Figure 9.1 illustrates how changes in diesel cost affect the profitability of BETs. In the figure, the diesel cost varies between 12 and 34 kr/l. At the current state, diesel costs approximately 16 kr/l, resulting in diesel trucks being the most profitable alternative, and it continues to be the most profitable alternative up to 17 kr/l, when instead BETs become the more profitable alternative, given that four trucks share the charging infrastructure. The other break-even points are 20 kr/l, where three BETs sharing the charging infrastructure become profitable, and 26 kr/l, when two BETs become profitable.

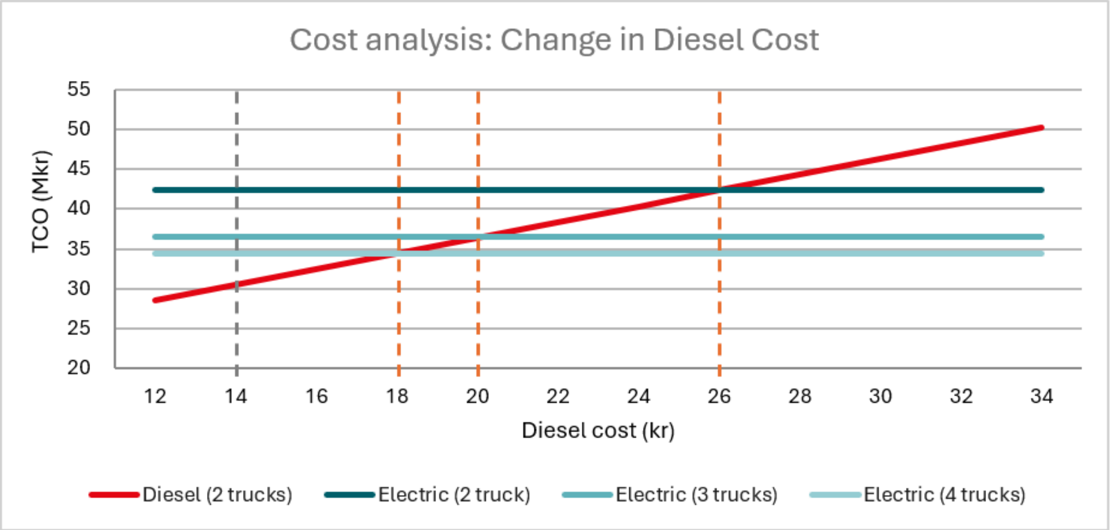


Figure 9.1: The change in TCO when diesel costs varies.

Figure 9.2 illustrates how changes in the private electricity cost affect the profitability for BETs. In the figure, the private electricity cost varies between 0.5 and 6.5

kr/kWh, and at the current state, the private electricity cost is estimated to be 2 kr/kWh. At this level, diesel trucks are the most profitable alternative. The first break-even point occurs when the electricity cost decreases to 1.5 kr/kWh, resulting in BETs becoming the most profitable of the four trucks that share the charging infrastructure. Subsequently, the next break-even point occurs at 1 kr/kWh, when three BETs share the charging infrastructure and are at this level more profitable than diesel trucks. Two BETs sharing the charging infrastructure do not become profitable in this case, even if the price of private electricity decreases to 0.5 kr/kWh.

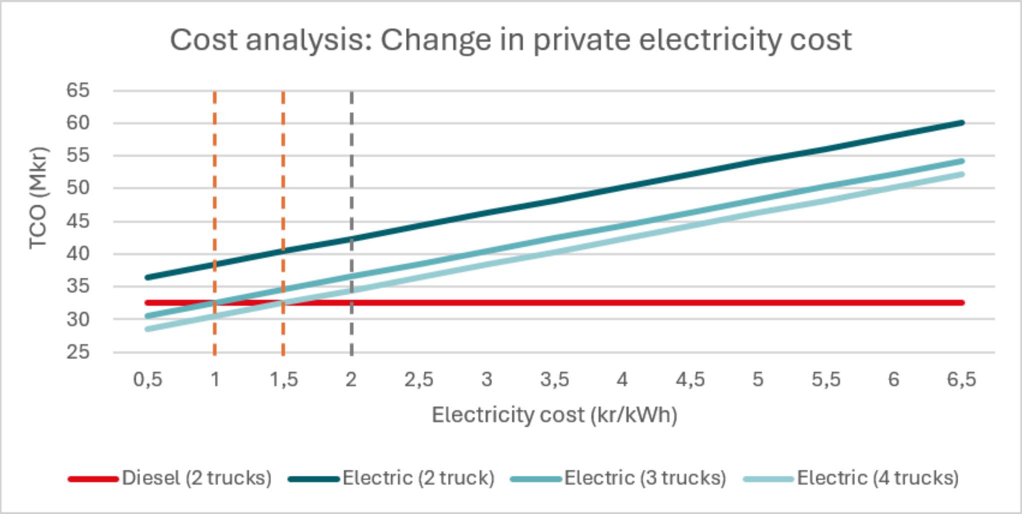


Figure 9.2: The change in TCO when the private electricity cost varies.

Figure 9.3 illustrates how changes in the public electricity cost affect the profitability of BETs if an 560 kWh public charger is used at Stop B, instead of an “in-house” built and owned 560 kWh charger. In the figure, the public electricity cost varies between 1.5 and 6 kr/kWh, and at the current state, the public electricity cost is estimated to be 4 kr/kWh. As can be seen in the figure, diesel trucks are the most profitable alternative, even if the electricity price decreases to 1.5 kr/kWh.

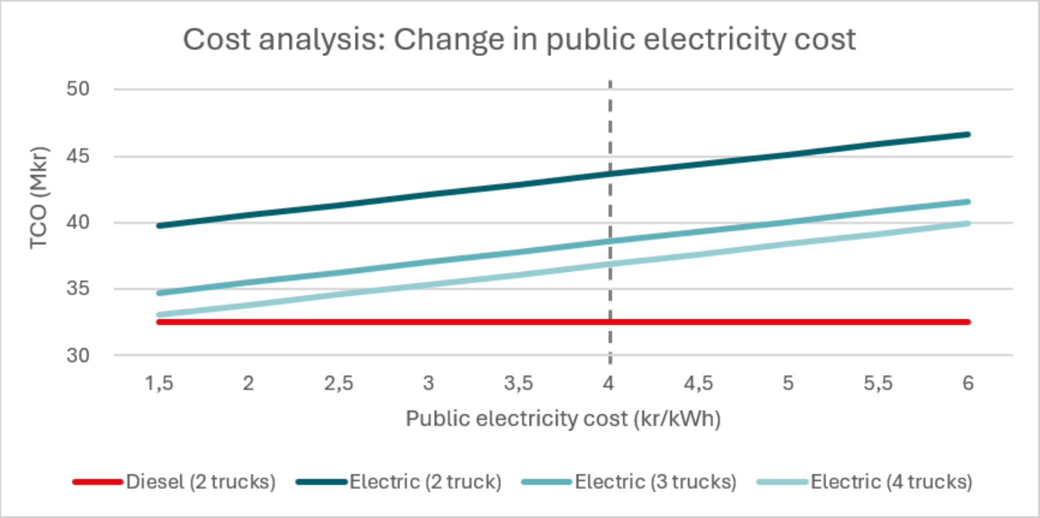


Figure 9.3: The change in TCO when the public electricity cost varies.

9.2.2 Residual values

Figure 9.4 and Figure 9.5 illustrate how changes in the battery and charger residual value affect the profitability of BETs. In the figures, the residual values vary between 0-25% and are expressed as a percentage of the purchase price. In the baseline of the TCO calculations the residual value is estimated to be 5% of the purchase price for both the batteries and chargers, meaning that diesel trucks are the more profitable alternative, and this is the case for the whole interval 0-25%.

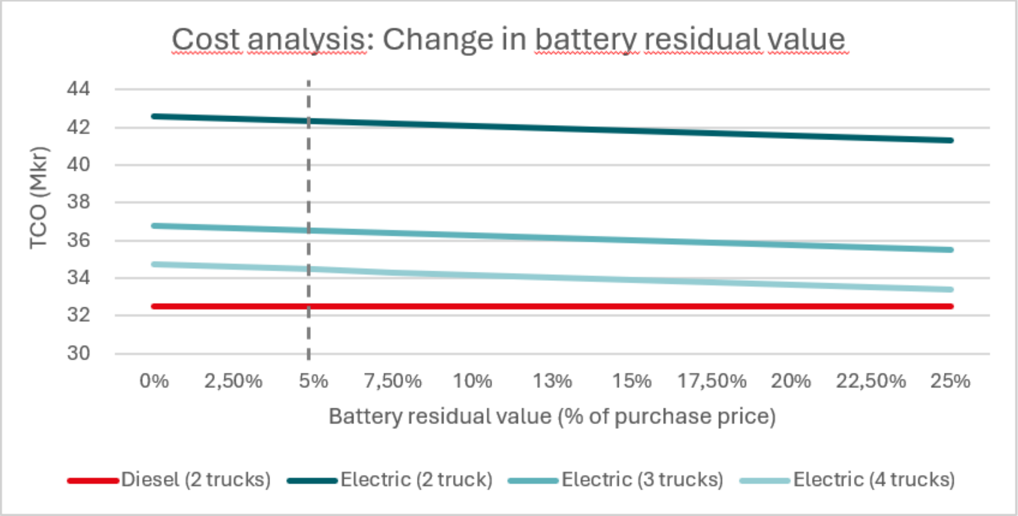


Figure 9.4: The change in TCO when the battery's residual value varies.

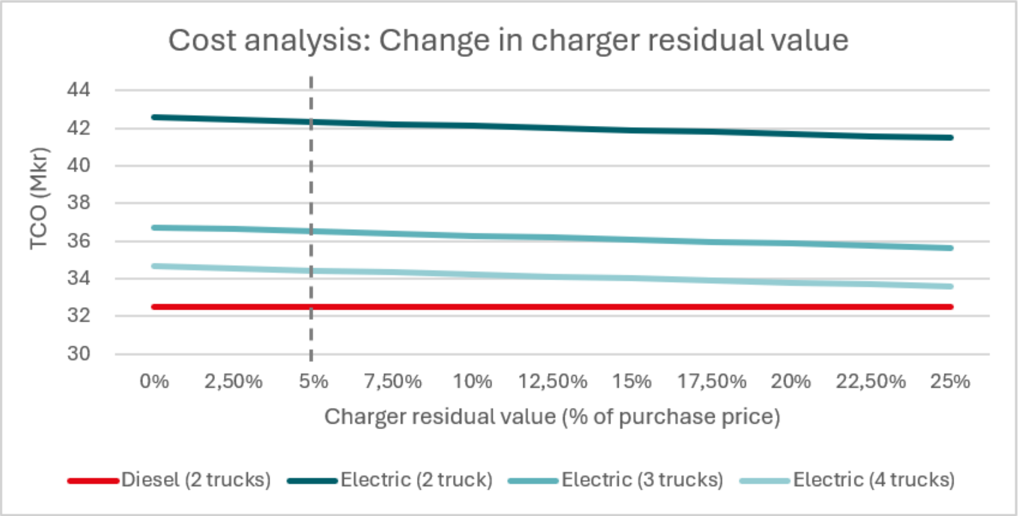


Figure 9.5: The change in TCO when the charger's residual value varies.

Figure 9.6 illustrates change in the diesel trucks residual value and how this affects the profitability for BETs. In the figure, the residual values vary between 0-20% and are expressed as a percentage of the purchase price. At the current state, the residual value for diesel trucks is estimated to be 15 %, and even if residual value decreases to 0%, the diesel truck remains as the most profitable alternative.

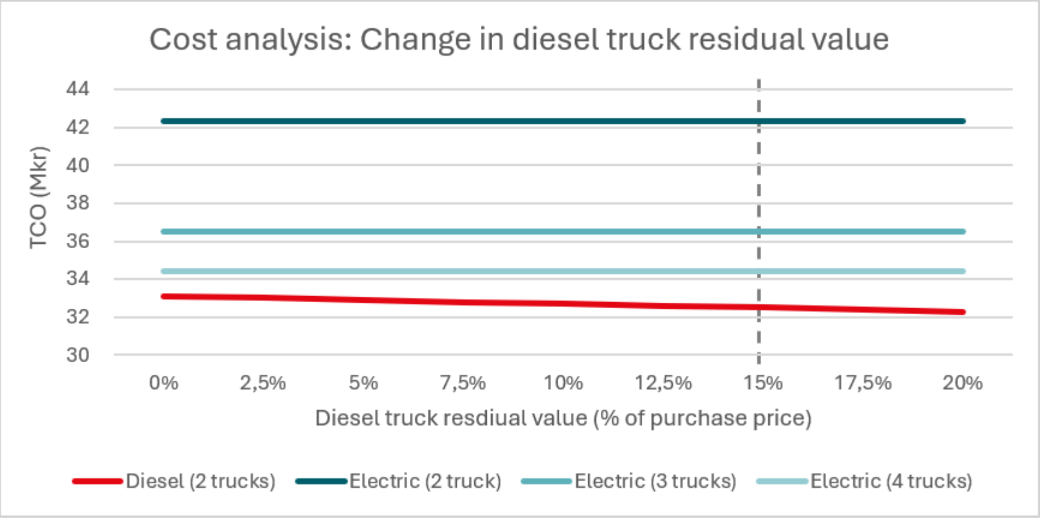


Figure 9.6: The change in TCO when the diesel truck's residual value varies.

9.2.3 Purchase price of batteries and chargers

Figure 9.7 illustrates how cost reduction for batteries and chargers affect the profitability of BETs. In the figure, the cost reduction for batteries and chargers varies between 0-50%, and the initial state is 0%, since the current cost of batteries and chargers is known, and the analysis aims to illustrate how a cost reduction of these variables affects the TCO. At the initial state of 0%, diesel trucks are the most profitable alternative, and this is the case up to the first break-even point occurring at 29%. After this point, BETs, with four trucks sharing the charging infrastructure, are the most profitable alternative. The second break-even point occurs when the cost for batteries and chargers decreases to 53%, after which three trucks sharing the charging infrastructure are also more profitable than diesel trucks.

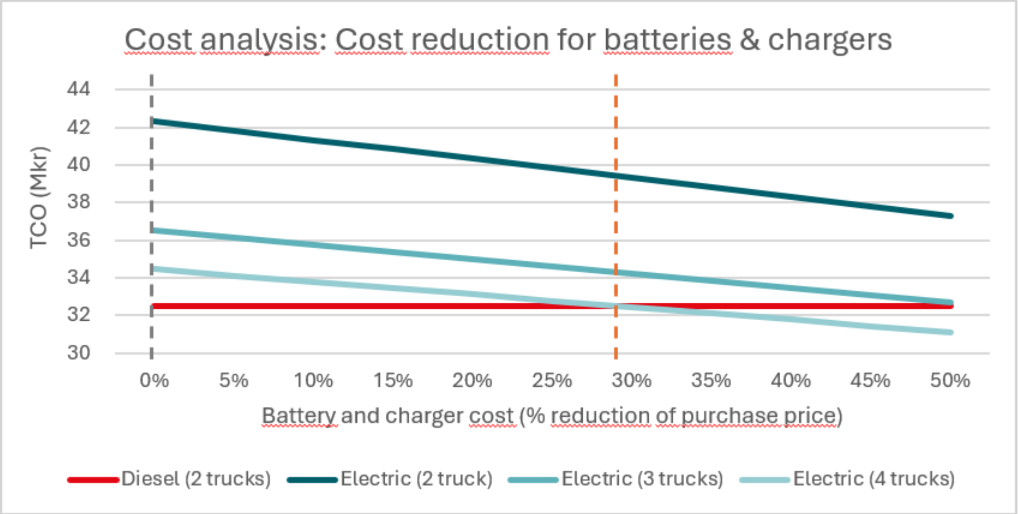


Figure 9.7: The change in TCO when the cost of batteries and chargers decrease.

9.3 Scenario analysis

This section presents three different scenarios of how the TCO changes for Route B if a combination of the different input variables of the TCO changes. The variables changed are based on the sensitivity analysis of the previous section, and this section presents the joint effects of several variables changing simultaneously. These scenarios are based on optimistic or pessimistic views on the future of the transportation system regarding electrification and diesel prices.

9.3.1 Scenario 1: Electricity optimistic & diesel pessimistic

Figure 9.8 and Table 9.1 illustrate an optimistic future scenario, where energy-related factors have developed favorably from a BET perspective. In this scenario it is assumed that all charging is done through privately owned chargers. The cost of electricity is lowered to 1,5 kr/kWh, due to investments in solar energy, BESS, or V2G-technologies. The residual value of batteries and chargers are assumed to increase to 15%, due to higher adoption of BETs in the system. The cost of diesel is assumed to increase to 25 kr/liter due to new policies and the residual value of diesel trucks have consequently dropped to 5% due to their high operating costs. The analysis shows that, independently of whether the chargers are utilized by two, three, or four trucks, the BETs are the most profitable alternative with a TCO that is 2.3 MSEK, 7.9 MSEK, and 9.9 MSEK more profitable compared with diesel trucks, respectively.

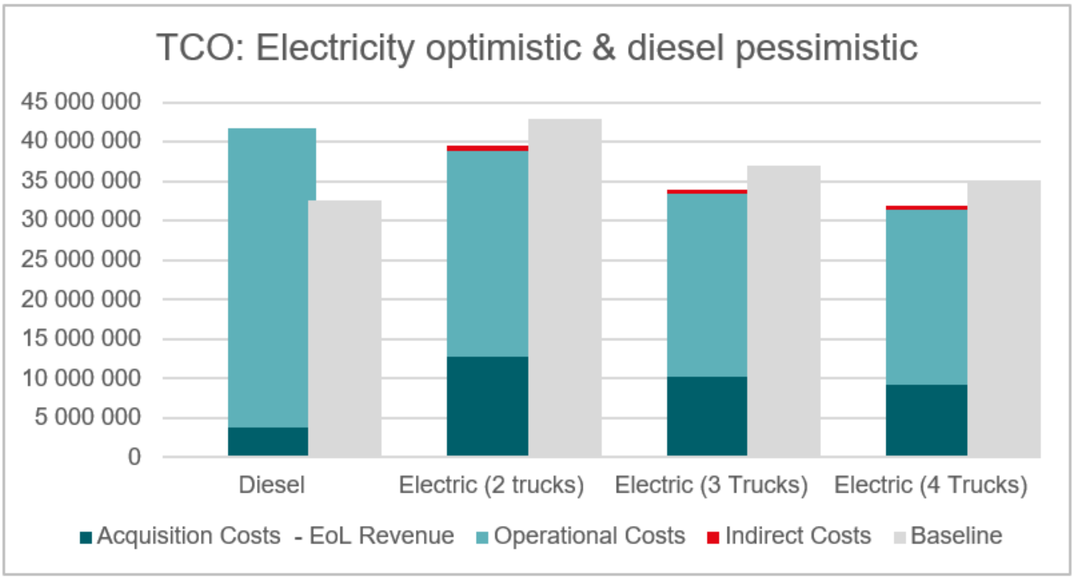
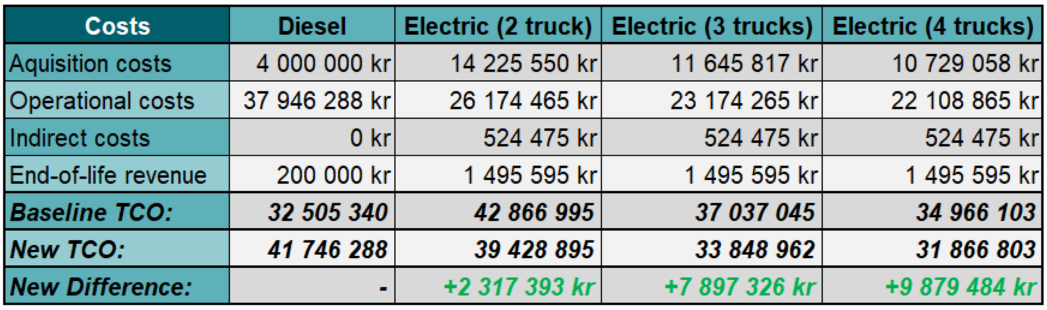


Figure 9.8: Electricity optimistic & diesel pessimistic TCO.

Table 9.1: TCO costs for electricity optimistic & diesel pessimistic scenario.



Costs	Diesel	Electric (2 truck)	Electric (3 trucks)	Electric (4 trucks)
Aquisition costs	4 000 000 kr	14 225 550 kr	11 645 817 kr	10 729 058 kr
Operational costs	37 946 288 kr	26 174 465 kr	23 174 265 kr	22 108 865 kr
Indirect costs	0 kr	524 475 kr	524 475 kr	524 475 kr
End-of-life revenue	200 000 kr	1 495 595 kr	1 495 595 kr	1 495 595 kr
Baseline TCO:	***32 505 340***	***42 866 995***	***37 037 045***	***34 966 103***
New TCO:	***41 746 288***	***39 428 895***	***33 848 962***	***31 866 803***
New Difference:	***-***	***+2 317 393 kr***	***+7 897 326 kr***	***+9 879 484 kr***

9.3.2 Scenario 2: Electricity neutral & diesel pessimistic

Figure 9.9 and Table 9.2 illustrate a future scenario, where energy-related factors are unchanged compared with today's levels. Diesel costs in this scenario are increased to 25 kr/liter, and the private charger at Stop B is substituted with a public charging with an 805 kWh charger. The analysis shows that BETs are the most profitable alternative if three or four trucks are utilizing the chargers, resulting in BETs being 2.8 MSEK and 4.5 MSEK more profitable compared with diesel trucks. If two trucks are utilizing the chargers, the TCO is 2.3 MSEK less profitable compared with diesel trucks.

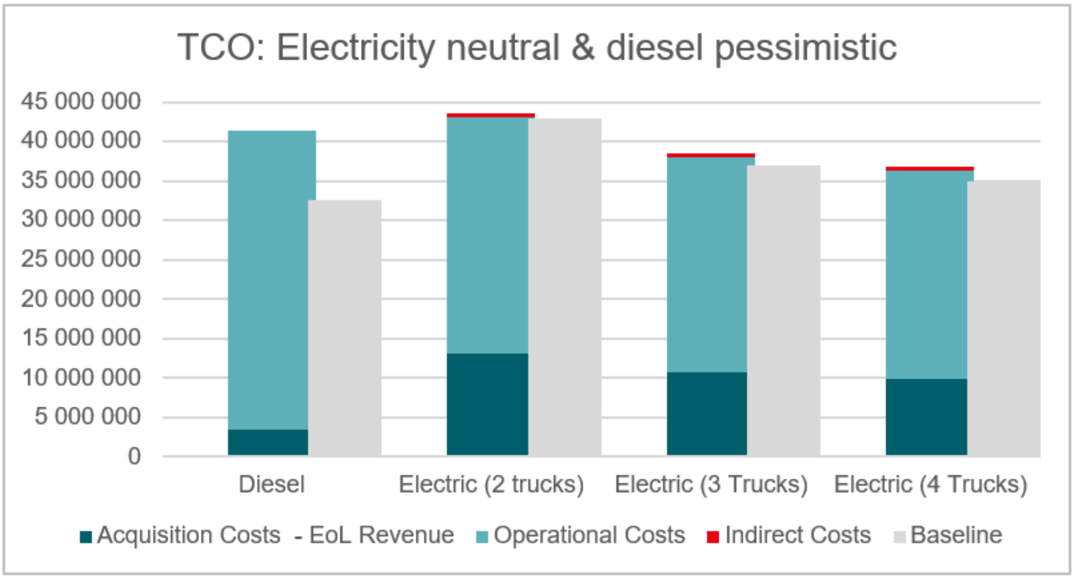
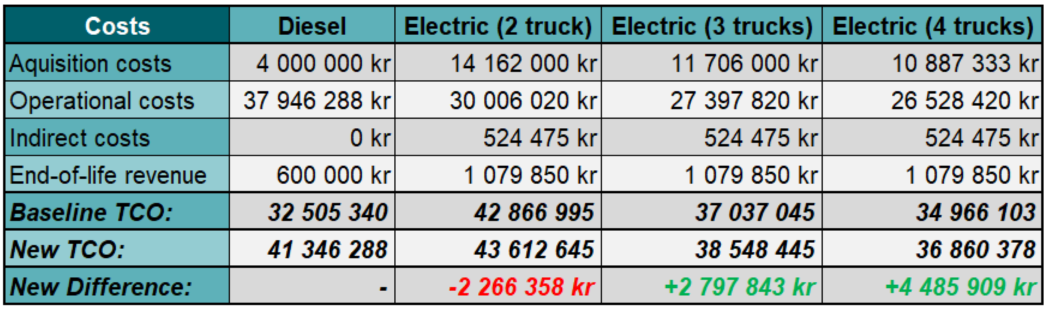


Figure 9.9: Electricity neutral & diesel pessimistic TCO.

Table 9.2: TCO costs for electricity electricity neutral & diesel pessimistic scenario.



Costs	Diesel	Electric (2 truck)	Electric (3 trucks)	Electric (4 trucks)
Aquisition costs	4 000 000 kr	14 162 000 kr	11 706 000 kr	10 887 333 kr
Operational costs	37 946 288 kr	30 006 020 kr	27 397 820 kr	26 528 420 kr
Indirect costs	0 kr	524 475 kr	524 475 kr	524 475 kr
End-of-life revenue	600 000 kr	1 079 850 kr	1 079 850 kr	1 079 850 kr
Baseline TCO:	***32 505 340***	***42 866 995***	***37 037 045***	***34 966 103***
New TCO:	***41 346 288***	***43 612 645***	***38 548 445***	***36 860 378***
New Difference:	***-***	***-2 266 358 kr***	***+2 797 843 kr***	***+4 485 909 kr***

9.3.3 Scenario 3: Electricity pessimistic & diesel optimistic

Figure 9.10 and Table 9.3 illustrate a future scenario where energy-related factors have developed unfavorably from a BET perspective, whereas factors associated with conventional diesel trucks have developed in a favorable way. The cost of electricity has increased to 4 kr/kWh, and the cost of batteries and chargers is assumed to have increased by 10% respectively. Public charging is used at Stop B, and private charging at the terminals. The residual value of batteries and chargers is assumed to remain unchanged at 5%, whereas the residual value for the diesel truck is increased to 15 %. Lastly, the diesel cost is also assumed to remain unchanged compared with previous levels used in the case, i.e., 16 kr/liter.

The analysis shows that diesel trucks are in this case always the most profitable alternative, and using BETs is 19.9 MSEK, 14.6 MSEK, and 12.8 MSEK more expensive, depending on whether two, three, or four BETs are utilizing the chargers.

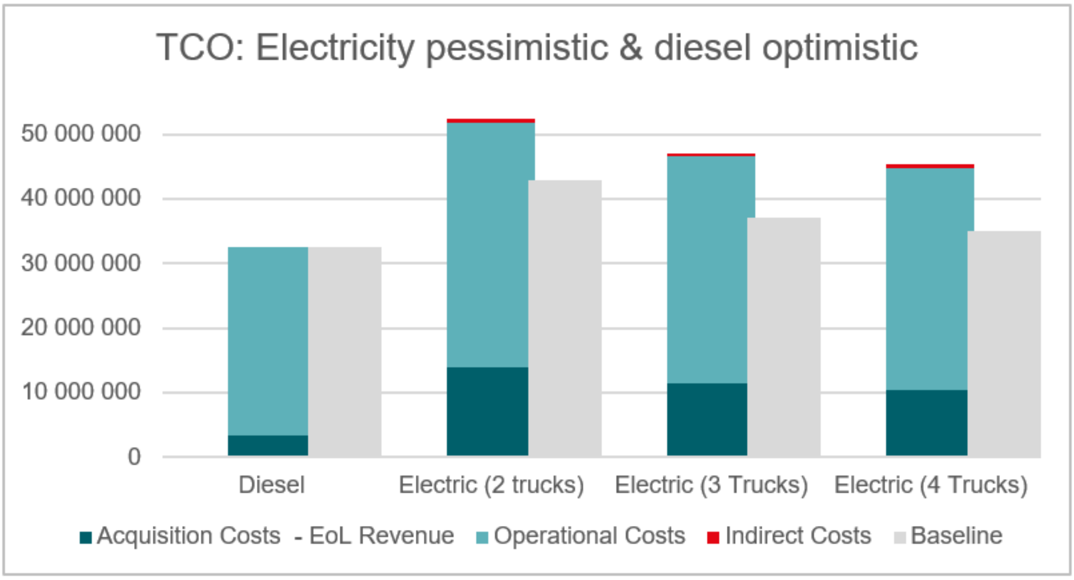
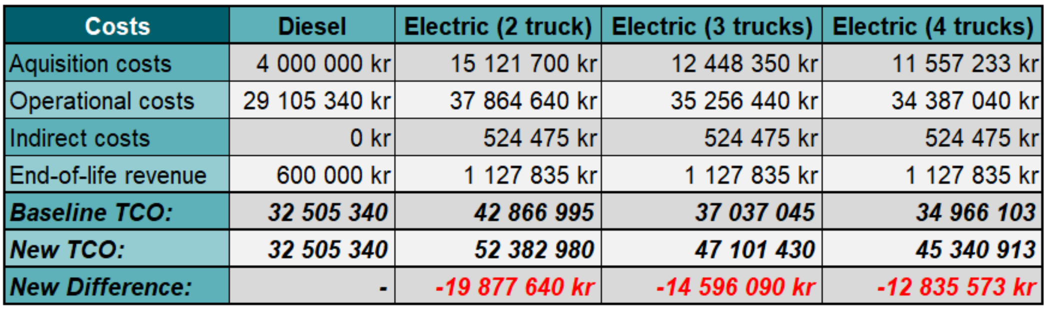


Figure 9.10: Electricity pessimistic & diesel optimistic TCO.

Table 9.3: TCO costs for electricity, in a electricity pessimistic, neutral & optimistic scenario.



Costs	Diesel	Electric (2 truck)	Electric (3 trucks)	Electric (4 trucks)
Aquisition costs	4 000 000 kr	15 121 700 kr	12 448 350 kr	11 557 233 kr
Operational costs	29 105 340 kr	37 864 640 kr	35 256 440 kr	34 387 040 kr
Indirect costs	0 kr	524 475 kr	524 475 kr	524 475 kr
End-of-life revenue	600 000 kr	1 127 835 kr	1 127 835 kr	1 127 835 kr
Baseline TCO:	***32 505 340***	***42 866 995***	***37 037 045***	***34 966 103***
New TCO:	***32 505 340***	***52 382 980***	***47 101 430***	***45 340 913***
New Difference:	**-**	***-19 877 640 kr***	***-14 596 090 kr***	***-12 835 573 kr***

9.4 Business network analysis

This section presents an analysis of empirical findings using the ARA-model. The ARA model provides a framework for understanding how the introduction of BETs leads to structural changes in the business network by highlighting the interdependence between the different activities, resources and actors in the business network.

9.4.1 Activities

The transformation to BETs in the line-haul operation creates and requires a significant shift in the activities in the transportation system. In the ARA-model, activities consist of the processes through which actors use and coordinate the resources and create value from them. In a traditional diesel-based transportation system, these activities are e.g., refueling, scheduling, maintenance, and route planning. These activities are subsequently performed in an infrastructure built around the diesel system, creating easy access to refueling and other activities. Moreover, these activities are also linked to each other, e.g., that the route planning activities are embedded with fuel scheduling, which also must align with other activities, such as stops for breaks and time windows for arrival at terminals. Additionally, activities such as maintenance usually align with the utilization level and are usually performed at occasions outside operation windows. Another thing that characterizes diesel-based systems is the greater flexibility, i.e. less need for coordination of route planning and fleet planning, compared with an electrified system.

The transformation to BETs yields an interdependent and challenging shift of the activity layers, and the most significant change is the implementation of charging, which replaces the activity refueling, but comes with more complex requirements. The refueling activity can be described as a decentralized and quick activity, whereas charging requires greater coordination, alignment with vehicle and route scheduling, and access to a currently not widespread and developed infrastructure. The charging activity is also merged with other activities in the system, including e.g., loading and unloading of the truck, and the mandatory breaks. This consequently acts as a constraint, permeating route and fleet planning. This illustrates the interdependence resulting from new activity links emerging, as described by Håkansson & Snehota (1995).

Furthermore, the transformation to BETs creates demand for additional activities surrounding the charging of the trucks. This includes optimizing the charging utilization, charging scheduling to match the transportation schedule, and the implementation of IT tools, thus enabling energy monitoring, as well as booking and payment solutions for charging. The values created from these activities are not only created independently in isolation, but also how they are linked to each other. Effective charging scheduling and management affect the utilization rates of the trucks, ensuring that the trucks do not need to wait unnecessary time for an available charger etc, which in turn is significantly important to achieve return on investment considering the high upfront cost associated with BETs. This illustrates the importance of a holistic view of the activities performed in the system, emphasizing integration and coordination.

The ARA-framework underscores how changes in activities affect and change other activities in the network. An example is the reduced operational flexibility which consequently affects route planning, in terms of operations on short notice, and switching route and delivery plans. In an electrified system, this is constrained by battery and charging availability and creates a ripple effect in the system affecting other activities. Increasing interdependencies and the complexity of the activity structure which increases the need for planning in advance.

In addition to the operational activities, the transformation to BETs also brings new activities of learning and innovation. Along with the interaction between actors to implement BETs, they perform activities in terms of knowledge sharing, experimentation, and business model adoption. These activities become particularly important in the early stage of such a transition, due to e.g., the uncertainty of the total cost of ownership, required maintenance, and battery degradation, associated with BETs. Thus, this illustrates that the activity layer is not only developed through technical replacement, from a diesel-based to an electricity-based system, but also through cognitive engagement and relationship development.

Figure 9.11 exemplifies the activity structure for an LSP who wants to introduce BET into their transportation network. This includes activities associated with deciding on which route to start electrifying, along with deciding on a hauler, and the decision on a charging strategy. The figure illustrates the activity links and the complexity of such a decision, and that it includes more than just the purchase of BETs and the associated chargers. Furthermore, the activities of battery sizing and charger sizing relate to an activity link, since the capacity of the charger and capacity of the battery are intertwined regarding the route planning and the profitability of the system. The charger sizing is in turn influenced by decisions and activities regarding the charging strategy and the battery sizing is influenced by the decisions made by the hauler. This highlights the complexity of the decision making and that it includes more than just the activities of purchasing BETs and chargers.

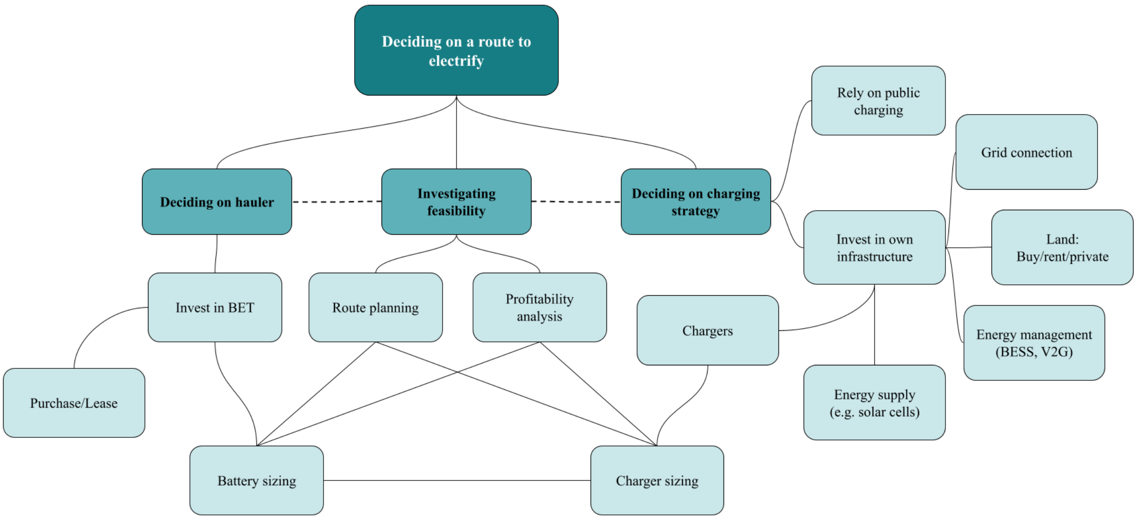


Figure 9.11: Activity structure for a LSP introducing BETs.

Furthermore, the transition does not only change what activities are performed in the system, but also how they are performed, and with whom they are coordinated. The charging infrastructure must be shared to achieve high utilization, and at the same time balance out the peak of demand, as well as minimizing downtime. All of which require alignment and interconnection of activities of multiple actors in the transportation network. The effectiveness of the transformation and subsequently the operation of BETs in line-haul operation will therefore be dependent on these active links, and actors' ability to build and manage resilient and well-functioning activity links.

To summarize, going from a diesel based to an electrified line-haul operation by introducing BETs, yields structural changes in the activity dimension in the ARA-model.

Both in terms of new activities emerging, including charging, energy and charging optimization, changes to existing activities, including route- and fleet planning, as well as increased interdependence among these activities. This follows the importance of managing the links between the activities in the network, since they play a key role in achieving efficiency and reliability in an electrified transportation system.

9.4.2 Resources

The transition and introduction of BETs in line-haul operations changes the resource structure within the network of the transportation system. According to the INA and the ARA-model resources are interdependent on each other through resource ties, and resources can be either tangible or intangible. In the current diesel-based system there are key tangible resources like diesel trucks, feuling infrastructure, terminals, drivers, and associated tools such as route optimization systems and planning tools. Furthermore, these tangible resources are complemented by intangible resources such as operational knowledge, experience, and business relationships with suppliers, partners, and customers. Among these tangible and intangible resources, there are some apparent examples of well-established resource ties such as the truck being reliant on the refueling infrastructure, drivers, terminals, and maintenance procedures. Resource ties that integrate different businesses and organizations with each other, creating business relationships and a well-developed system with strong resource ties.

When introducing BETs into this well-developed resource constellation system it disrupts the system, since new resources are introduced, old ones are replaced, and the resource ties shift. BETs are significantly different from the traditional diesel trucks, relying on the resource of electricity and charging infrastructure instead of diesel fuel and refueling infrastructure. Electricity as a resource is dependent on the energy supply which is, at least currently, less stable compared to diesel as a resource. Consequently, the value of a BET is not solely inherent, but it depends on how it is supported by and combined with other resources, such as the battery, chargers, grid infrastructure, and energy supply. This highlights that resource heterogeneity is a central point according to the INA and ARA-model, since the value of the resource is influenced by its coordination and combination with other resources.

There is a strong resource tie between BETs and chargers, since their individual value is highly dependent on the other resource. A charger is pretty much useless without a BET utilizing it and a BET is useless without a charger. This is further strengthened by how much the utilization of chargers influences profitability in the case results. The introduction of BETs is therefore reliant on the development of charging infrastructure, which in turn is dependent on other tangible resources like grid connection, land, and energy supply, which is influenced by resources like solar cells, BESS, or V2G systems. One key challenge highlighted in the empirical findings is that establishing grid connection can be a lengthy process which in turn delays the possibility to introduce a BET on a line-haul route, due to the resource ties between the BET, charger, and grid connection. This is made even more complex since the required grid capacity and charger capacity depends on the BET's battery, which in turn depends on the transportation assignment. These dependencies create more complex interactions compared to the diesel truck, as previously mentioned in the activity section.

The transition to BETs also increases the importance and expands the role of intangible resources. Knowledge related to the new tangible resources and understanding how these resources relate to each other and how they integrate into the current system becomes important. For example, capabilities and knowledge of route planning will also require an understanding of how energy consumption profiles, charging strategies, or energy supply strategies will influence the route planning. As highlighted in the empirical findings, competence related with digital tools and supportive IT-system becomes more important, since the new resources depend on real-time data flows such as price of energy. The knowledge and understanding of these changes to the system can be accessed through sharing knowledge with other actors, through the intangible resource of a business relationship. Furthermore, IT-system and digital capabilities need to be co-developed within the relationships of actors that might not be traditionally adjacent. Relationships as a resource thus become important to both gain knowledge and develop capabilities in the network. Another important aspect of the relationships relates to the ability to coordinate investments as well as the trust, alignment, and communication between different actors such as haulers and LSPs, something that was highlighted in the empirical findings. Figure 9.12 illustrates the resource ties within the electrified transportation system when introducing BETs. At the core are key physical and digital resources, such as BETs and charging infrastructure that are interconnected through various resource ties. Surrounding and enabling these resources are the intangible resources of knowledge and business relationships, since these influence the ability of actors to access, combine, and develop the core resources.

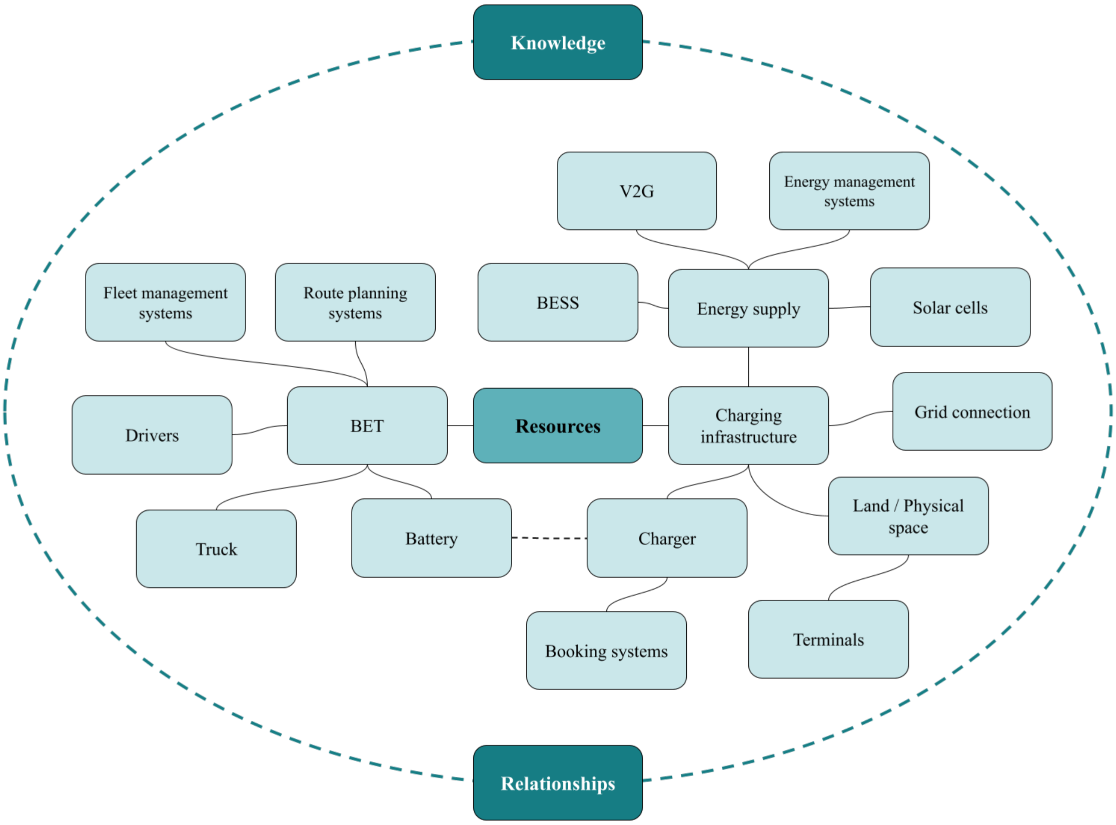


Figure 9.12: Illustration of the resources ties between the resources in the electrified transportation system.

A large-scale transition towards BETs can also mean that some of the traditional and current resources will lose relevance or value. The residual value of diesel trucks might fall, or competencies related to mechanical maintenance may decline in importance, impacting the different actors in the network.

In summary, the introduction of BETs reshapes the resource dimension of the network by introducing new resources, retiring old resources, and changing the resource ties between the intangible and tangible resources through new combinations and coordinations. The system becomes more interdependent, with an increased emphasis on knowledge and business relationships.

9.4.3 Actors

As BETs are introduced in line-haul operations, the structure of actors and actor bonds will change. According to the INA, actors are the ones to govern and control resources and perform activities, and as described in the two previous subsections, changes in the activity structure and resource structure will have a ripple effect on the actor structure. In the conventional diesel-based system there is a relatively stable set of actors with well-established roles. Haulers operate the vehicles and perform the transportation activities. LSPs coordinate routes, assign transportation tasks, manage terminals, and perform joint loading activities like cross docking. Fueling infrastructure providers ensure access to fueling to both truck- and car drivers. These actors' interactions are based on a long-standing logic of operational efficiency, cost control, and reliability. The actor bonds in this context is more transactionally focused for each actor, with cooperation centered around service delivery, vehicle use, and maintenance to optimize operations and reduce system costs.

Introducing BETs into this system requires actors to change their roles and relationships. The transition to BETs will also require an expansion in the number of actors involved and the need for collaboration between the actors. New actors associated with energy supply, charging services, digital infrastructure, and vehicle technologies need to be introduced and become more important for the network. The collaboration and cooperation between all actors need to extend beyond its traditional transactional nature, such as LSPs collaborating more closely with haulers by having longer contracts to ensure financial safety and improve the cost profile of the BET through increased utilization. Similarly, new partnerships between LSPs as terminal operators and energy suppliers to enable private charging and energy management systems, require collaboration. The introduction of BETs will require the actor bonds in the system to become stronger, with actors having closer and more long-term relationships to collectively manage uncertainties regarding costs, technology developments, and charging infrastructure. Actor bonds that are characterized by greater mutual dependence and shared interest in long-term system development.

The roles of the current actors in the network also need to change and adapt. LSPs, for example, can no longer only be coordinators of transportation flows but may need to take a more active role in planning investments, allocating charging infrastructure, or managing partnerships with technology providers. Haulers need to adapt so that they can manage their own charging infrastructure as well, needing to engage in energy procurement, and make strategic technology choices. Refueling providers traditionally concerned with the supply of diesel also need to adapt by offering charging infrastructure, developing booking systems, and managing their energy. The boundaries between actor roles might blurry since all these actors now need to manage charging infrastructure, reflecting a shift towards a more interconnected network.

New actors such as OEMs of chargers, digital service providers, battery management companies, and energy companies will be introduced to the network, expanding the boundaries of the traditional network. The influence of these actors will grow as more and more BETs are introduced since BET operations become increasingly reliant on data exchange regarding e.g. energy prices or charger availability.

The coordination of actors around these new roles requires not only contractual agreements but also shared understanding and aligned objectives. It is also important to note that this transformation of the actor network and its roles creates asymmetries in power, knowledge, and influence. Some actors are more well equipped to make adaptations and change their role, while others can struggle to respond to the change in demands. This difference between different actors can create tension regarding responsibilities and how these should be distributed. E.g. smaller hauler firms might have a hard time covering the high investment costs of BETs unless contracts are extended or if charging can be made affordable at terminals or with customers. If the current actor bonds are transactionally focused it can create tensions on the smaller companies expected to carry these large investments. Having more aligned objectives will be crucial for overcoming this and the success of the transition.

To summarize, the network of actors will need to be reshaped when electrifying line-haul operations using BETs. It will require new and closer relationships between the different actors and the roles of different actors will be reconfigured. Some traditional actors need to change their roles or risk being replaced. New actors will be necessary to facilitate the transition. The outcome and success of the transformation will depend on the actor's adaptability and the quality of their actor bonds to coordinate and combine their resources and activities in a way that promotes a more environmentally friendly logistic system. An illustration of the key actors in the transportation system and their relationships are illustrated in Figure 9.13. These actors are interconnected through actor bonds within the transportation system as well as connected with other actors beyond the transportation system, highlighting the complex nature of the business network.

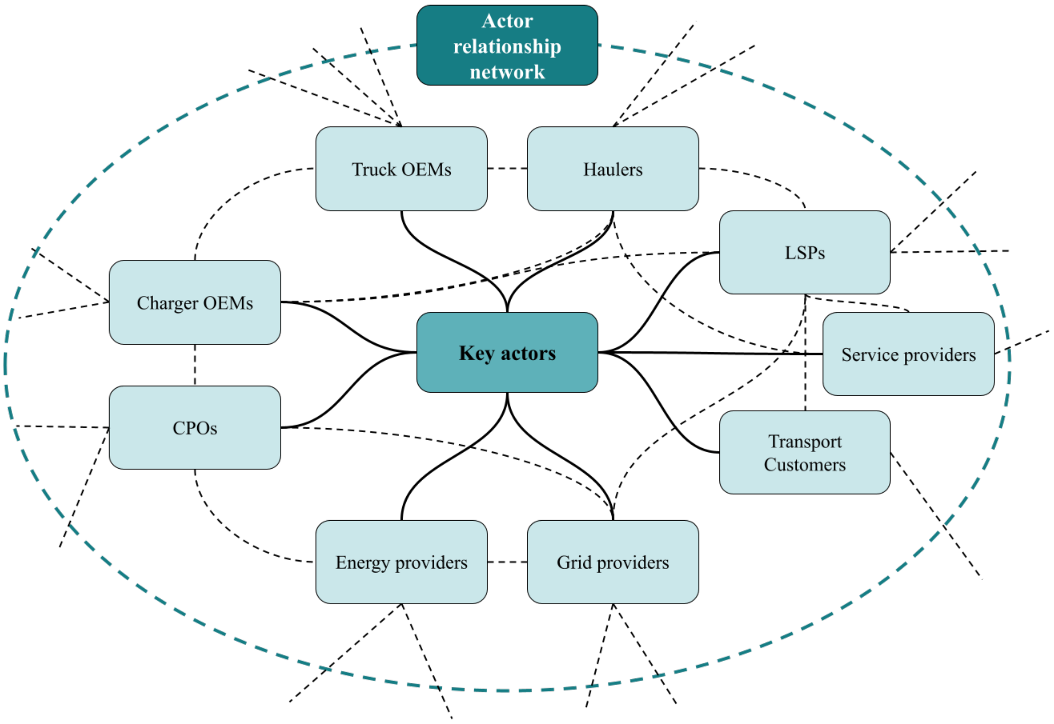


Figure 9.13: Illustration of the actor bonds between the actors in the electrified transportation system.

10

Discussion

The empirical findings show the conflict between technical feasibility and operational logic. This is the case for Route A, which is characterized as a short line-haul route, and still faces obstacles from operational standards. This is because Hauler A uses older trucks for these routes, since they are more likely to break down and operating them on short routes makes potential breakdowns less costly due to lower downtime. Consequently, a route that is technically feasible is least favorable for BETs from Hauler A's operational perspective. This illustrates the misalignment between operational logic and technical feasibility, i.e., short routes which at first sight look optimal for BETs due to less range constraints, are instead least desirable to electrify due to their operational functionality. Furthermore, these short routes are more dependent on the utilization of the truck on its second shift as a distribution vehicle to become profitable.

Furthermore, the haulers expressed the need for collaboration to succeed with this transition, and they have a common view that the responsibility for the transition lies solely on them. The haulers also highlighted that they are limited by the low margins, making the large upfront cost for both BETs and charging infrastructure a significant constraint for them to transition. Another factor, not explicitly mentioned in the empirical findings, is the fact that haulers usually rent their terminals and garages, hindering them from installing their own charging infrastructure at the facilities where they are operating, amplifying their inability to perform this transition without collaboration.

The aforementioned indicate the prevailing systematic requirement, cooperation between actors. Haulers emphasize the need for LPSs, such as DB Schenker, to provide affordable charging infrastructure, e.g., by installing chargers at their facilities, and offer charging at favorable prices. This would mitigate the financial burden otherwise carried by the haulers and ease the transition for them.

The sensitivity analysis in section 9.2 showed that the electricity and diesel prices have a significant impact on the profitability of BETs. In contrast, the residual values for both batteries, chargers, and diesel trucks have a minimal impact on the profitability of BETs. Furthermore, the scenario analysis in section 9.3 illustrates different possible future scenarios, depending on in what direction the critical factors develop. With an optimistic view from a BET perspective, BETs can become the most favorable alternative, given that the electricity prices remain at current levels or lower, and the diesel price slightly increases. Instead, if electricity related factors worsen, as in the pessimistic scenario, the diesel trucks will remain the most profitable alternative. However, the optimistic scenario is arguably a scenario that aligns with sustainability trends, technical development, and political interventions. For example, many currently see new technologies and opportunities that are favorable from a BETs perspective, such as V2G and BESS, which are technologies with the possibility to decrease the electricity cost. Furthermore, the pioneer Falkenklev is an example of an actor taking initiatives for implementation of BETs, by building charging infrastructure which others can utilize, and solar panel farms to achieve low and predictable electricity cost. Their transition also showcased the importance of subsidies, since they expressed that this would not be possible without public funding, thus emphasising the need for financial support at the early stage of the transition.

The scenario analysis illustrated that the profitability of introducing BETs in a line haul operation can vary greatly depending on how critical factors change in the future, and what scenario to prepare for depends e.g., on sustainability trends in society, the technical advancement, and the political view and the interventions of policymakers. An example of one such intervention is the new EU Emissions Trading System (EST2) that will start in 2027 (Naturvårdsverket, n.d.). This will make it so that fuel distributors will have to purchase carbon allowances for the CO_2 emissions associated with diesel, possibly increasing the price of diesel in Sweden with 2,5 kr/liter (AIP, n.d.).

Moreover, the TCO results show that the utilization of both BETs and chargers significantly influence profitability, highlighting the importance of striving to maximize this. Especially when it comes to a network of MCS-charging, high utilization of such a network then becomes a critical enabler for it to be both feasible and profitable to introduce BETs in a line-haul operation. In addition to the charger utilization, the batteries must be developed so that the long routes can be managed without disrupting the transportation and delivery scheduling, and such batteries are, according to industry experts, not far from being reality. As the case result showed, having a larger battery can be more cost effective, compared with implementing an extra stop for charging in the transportation schedule. However, opting for a large battery is under the assumption that weight is not a limiting factor.

Although the residual value for BETs and diesel trucks impacted the TCO significantly less compared with electricity and diesel cost, it arguably remains an important factor. In the analysis, the initial value for the residual value was assumed to be 5 % for both BETs and diesel trucks. There is, however, a risk that the diesel truck depreciates much faster than that, due to regulatory obsolescence, as well as the BETs residual value exceeding well beyond 5%. Thus, this underscores the importance of how sustainability trends develop, as well as the political view and interventions.

It is also important to consider customers' willingness to pay, and currently customers have relatively low willingness to pay extra for green logistics, as mentioned by e.g., Hauler B and DB Schenker Åkeri. Without a strong demand for green logistic solutions and regulatory support results in lower incentives for the haulers to pursue this transformation.

As explained in section 9.4 in the analysis, the transition to BETs in line-haul operations is not merely a technological switch where diesel trucks are switched with electric ones. The transition will fundamentally restructure the network in terms of its activities, resources, and actors. At its core, the BETs will require new ways of planning, coordinating, and executing transportation assignments since the switch from refueling to recharging poses more intricate synchronization with route planning in terms of rest periods, loading and unloading, as well as charger availability. This creates a more interconnected structure of activities and increases system complexities, amplifying interdependencies between actors. Consequently, the intangible assets of knowledge and business relationships become crucial resources to understand how to transition to BETs effectively, since the ability to understand how to adopt new technologies, gain access to infrastructure, how to share data, and how to manage risks together with other actors becomes crucial for the success of the transition. For example, the transition to BETs also requires the adoption of new IT tools like energy monitoring, charging scheduling, and payment methods, all of which further increase the importance of collaboration between and standardization across actors. The success of these systems depend on the alignment among the actors, based on their shared understanding and mutual adaptation. Consequently, gaining knowledge from different actors' perspectives and sharing knowledge with each other impacts the potential of these emerging technologies.

Actors like DB Schenker Åkeri, Hauler C, and Falkenklev, have deliberately adopted BETs to learn about their operational implications, highlighting how experimentation and learning-by-doing can help with building knowledge which is important in this early phase of the transformation. Furthermore, initiatives and research projects like E-Charge or REEL become crucial for facilitating this knowledge development and exchange, through both vertical and horizontal collaboration. Collaborating in projects like these will help in strengthening both knowledge and collaboration in the business network.

Actors that act early in this transformation may unlock several first-mover advantages such as establishing charging infrastructure more easily. By owning the charging infrastructure at locations like terminals it allows for more control over the system, by for example supplying the chargers with energy through solar cells or BESS reducing uncertainties related to electricity costs, as previously mentioned. Establishing chargers in other key locations such as refueling stations or logistics hubs allow for new business models for the actor establishing chargers there, e.g. actors like CPOs. Delaying action of transitioning to BETs, on the other hand, could result in missed strategic positioning. Late adopters may risk being excluded from the charging infrastructure if demand for charging increases faster than the development of infrastructure. The long lead time for grid connections indicates that this is already an issue, suggesting that if an actor is late to take action it could lead up to two years of delay. Being late could also impact the opportunities for knowledge development and relationship building. These risks strengthen the need for a clear strategy and future vision, as previously mentioned. As highlighted in the scenario analysis, the future shapes will have a large impact on the profitability of the diesel system and the BET system. The risk of being late and the uncertain future necessitates having a clear vision and strategy for the future.

The future of the transportation system is influenced by policy and the decisions made by policymakers and industry leaders. As previously mentioned, and highlighted by Falkenklev, the role of subsidies and public investments can be crucial in the early stages of the transition, allowing for investments that would not be possible otherwise. Without significant financial support, the upfront costs of BETs and associated infrastructure can be barriers that are hard for most haulers to overcome. Consequently, development of charging infrastructure also needs to be prioritized by industry leaders if they want to support the transition. Furthermore, the future cost of diesel and electricity is directly influenced by the decisions made by policymakers, meaning that they can incentivize the phase-out of diesel trucks and the adoption of BETs. The decisions made by each individual actor in the system should therefore not be made and viewed in isolation, since the impact of their decisions will influence other actors. Understanding the business network and its dynamics when changes are made to its activity, resource, and actor structure is therefore essential for a successful transition.

11

Conclusion

The aim of this report was to analyze the possibilities and barriers associated with the introduction of BETs in DB Schenker Nordics's line-haul operations. With the purpose of examining how different line-haul routes can differ in terms of feasibility and profitability, which was subsequently broken down into four research questions. The conclusion of each research question is presented in the following subsections 11.1-11.4. Finally, subsection 11.5 combines the conclusions of each individual research question to give the final conclusion of this report.

11.1 RQ1 - Technical feasibility

The first research question of this report was as follows: *"What influences if the introduction of BETs on a line-haul route is technically feasible?"*. The pre-study and the empirical findings indicate that the key factors influencing technical feasibility are battery and charger capacities. The required capacities for introducing BETs on the analyzed routes exceed what is currently available, but according to industry experts these capacity levels are expected to be available within the next 5 to 10 years. It is therefore important to adopt a forward-looking perspective, as battery and charger size is improving and the constraints are unlikely to remain a limiting factor in the future. Despite this, certain operational limitations, such as volume and weight constraints on specific routes, may still pose challenges when technology advances. Nevertheless, these routes can still be electrified through alternative operational strategies, such as deploying additional trucks or incorporating extra charging stops. Thus, while technical feasibility can often be addressed, the more pressing question becomes whether BET introduction is economically viable, which is explored in RQ2.

11.2 RQ2 - Profitability of using BETs on different routes

The second research question of this report was as follows: *"How does BETs compare to diesel trucks in terms of total cost of ownership for different types of line-haul routes?"*. Based on the results of this report, the profitability of the BET system is negative compared to the diesel system when there is low utilization of both the truck and the chargers in the system, which was the case for all three of the case routes in the case study. The longest route of case C achieved the highest truck utilization which reached positive profitability when combined with high charger utilization. However, this route was not technically feasible to introduce BETs under the conditions of fitting into the current driving schedule and having a 1050 kWh battery. Stopping for extra charging in this case was less profitable compared to installing a larger battery, highlighting that the indirect cost of loss in operational flexibility is larger than the extra acquisition cost for a larger battery. The profitability of the shorter routes of cases A and B are influenced by the truck utilization outside of the line-haul operations, meaning that these are less profitable in isolation to introduce BETs on.

11.3 RQ3 - Profitability factors

The third research question of this report was as follows: *"What are the critical factors that influence the profitability of introducing a BET on a line-haul route?"*. The case result showed that truck and charger utilization were critical factors influencing profitability and the sensitivity analysis showed that the cost of diesel and the cost of electricity were the factors that influence profitability the most. The scenario analysis highlighted how impactful changes to these critical factors were, with BETs outperforming diesel trucks in the electricity optimistic scenario 1 but drastically underperforming the diesel optimistic scenario 3. The factors of truck utilization, charger utilization, and electricity cost can be influenced by the different actors in the transportation systems business network. A more widespread adoption of BETs can increase charger utilization significantly, truck utilization can be increased significantly by driving long distances during the distribution rounds, and electricity costs can be reduced by investing in energy supply technologies. The cost of diesel can, and will be influenced by the decisions of policymakers. Consequently, the development of these critical factors can be influenced by the business network of the transportation system, connecting to RQ4.

11.4 RQ4 - Business network

The fourth research question of this report was as follows: *"How does the introduction of BETs in line-haul operations influence the surrounding business network of the transportation system?"*. As the ARA analysis shows, the introduction of BETs in a line-haul operation reshapes the interconnected business network by introducing new activities, resources and actors. Charging is a new activity that replaces refueling of diesel, which is an activity requiring more planning and coordination, both of resources and actors. The resources shift from diesel related to charging infrastructure, yielding increased interdependence between BETs, chargers and the energy grid. These increased complexities require increased knowledge development and sharing, cooperation and closer relationships between actors in the network.

Overall, the introduction of BETs in line-haul operation demands stronger collaboration to ensure a successful transition. Besides the importance of cooperation, it is also important that each actor individually takes their responsibility to ensure a successful transformation, including, e.g., building charging infrastructure for other actors to utilize, and not having a holistic view by thinking that other actors should make the transition. Additionally, from a business perspective, it is important to have a proactive approach, to make sure one is not trying to adapt to the transition too late, thus missing out on business opportunities, as well as avoiding the risk of delaying the introduction further due to long lead times of e.g, grid connection.

11.5 Matrix for introducing BETs

The conclusion from this thesis is that the introduction of BETs in line-haul operations highly depends on profitability, technical development, operational feasibility, and the interplay between actors in the business network. The feasibility of introducing BETs on a line-haul route depends on the technical feasibility in terms of battery- and charger capacity as well as the operational feasibility for the specific route in terms of volume, weight, and the operational structure. These feasibility factors are influenced by the surrounding business network. The profitability of introducing BETs on a line-haul route depends on the critical profitability factors previously mentioned and the business structure of the route. These profitability factors can also be influenced by the surrounding business network. The introduction of BETs in line-haul operations depends on the relation between feasibility and profitability, as illustrated as a 2x2 matrix in Figure 11.1.

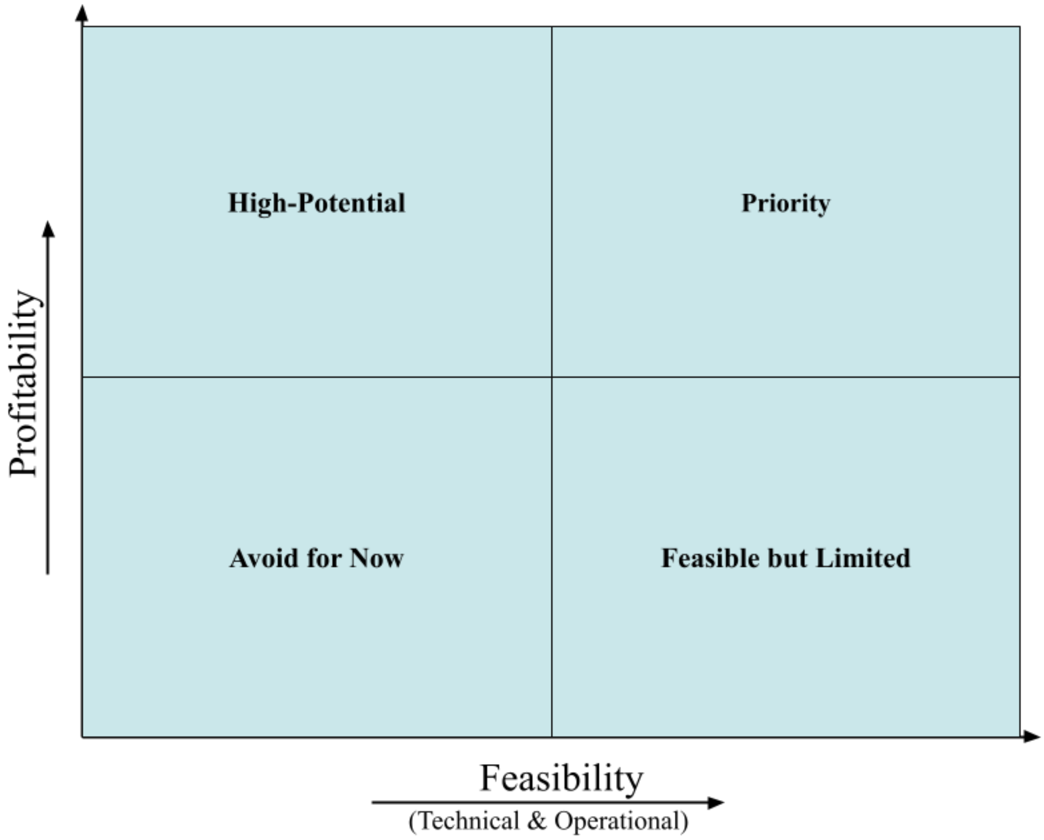


Figure 11.1: A 2x2 matrix illustrating the relation between profitability and feasibility of introducing BETs in a line-haul operation.

Line-haul routes that are both feasible and profitable to switch to BETs can be seen as “priority initiatives” since the barriers for introduction are small and it will be profitable to switch. “High-potential” are routes that would be profitable but limited in terms of feasibility, due to e.g. limited battery capacity, charging infrastructure, lack of operational fit, or weak relationships with key actors. “Feasible but limited” routes are projects where the feasibility factors are high, but the profitability is low. Moving these to the priority quadrant would require changes in the profitability factors, such as improving truck and charger utilization or changes in electricity or diesel costs. Routes that are neither feasible nor profitable are categorized as ”avoid for now”, which would require changes to both the feasibility aspects and the profitability factors to become profitable. For example, these types of routes might require technological development or changes in the operational schedule to become more feasible, as well as changes in the profitability factors such as increased truck and charger utilization or increased diesel costs. From the case study, all three routes currently fall under the “avoid for now”. However, as illustrated in this report this can change in the future depending on the technical development, decisions of policymakers, and the initiatives from the actors in the surrounding business network.

11.6 Future research

Future research could analyze the feasibility of using charging infrastructure at DB Schenker´s bypassing facilities, instead of e.g., building charging infrastructure along the route which would require acquisition of land. By analyzing this, an understanding can be gained of whether it is worth it to drive an alternative route to reach a charger at a DB Schenker facility, instead of acquiring and building charging infrastructure beside the main route. Furthermore, future research could also delve into the holistic usage of BETs, including all the routes and distribution rounds the BETs perform. This would yield a greater understanding of how introduction of BETs affect the TCO, in relation to diesel trucks. Moreover, analysis should be made whether 1050 kWh is the optimal battery size in terms of flexibility and price. Lastly, the subject of the introduction of BETs in the transportation network is a broad scope, including a variety of aspects to consider. This thesis points out some key factors and challenges of this transformation, however, there are many more levels of analysis to be made, to point out other factors and challenges. Thus, future research should therefore include other scopes, such as analysis on a fleet, country-level and EU-level, beyond the analysis of this report of specific routes.

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