Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

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A TCO Analysis of the Transition to Battery Electric Trucks in Norway

Master's thesis in Industrial Economics and Technology Management
Supervisor: Steffen J. Bakker
Co-supervisor: Anne Neumann
June 2023

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Preface

This thesis concludes our Master of Science in Industrial Economics and Technology Management (IØT), with specialization in Financial Engineering, at the Norwegian University of Science and Technology (NTNU). It was written during spring 2023 and is a continuation of our project thesis (TIØ4550) written during autumn 2022.

We want to thank our supervisors, Steffen Bakker and Anne Neumann, for their insight and guidance throughout this project. We also want to thank Thorleif Foss and Dag Nordvik in NLF (The Norwegian Trucking Association) for helping out with data collection and understanding of the trucking market. We would also like to express our gratitude to Frode Rømo in Sintef Industry for useful input and discussion.

Jenny Heggen Thiis and Solveig Hegstad Krüger

Trondheim, 10th June 2023

Abstract

In this thesis we investigate how the decision to invest in battery electric trucks (BETs) is affected by uncertainty in terms of fluctuating energy prices, declining capital costs, and infrastructure development. Moreover, we look at how the investment decision changes over time for different types of trucking companies. We then explore how the government can accelerate the transition to zero-emission road freight by introducing new support schemes and subsidizing infrastructure investments.

We do a comparative analysis of the total cost of ownership (TCO) for BETs and diesel trucks (DTs), focusing mainly on the investment years 2023 - 2033. We then expand with a high-level analysis between 2034 - 2040. The TCO is calculated using Monte Carlo simulations, where the electricity and diesel prices are underlying stochastic processes. Refueling inconvenience is used as an additional cost component for BETs to represent the inconvenience that the current level of charging infrastructure gives. We consider three scenarios for infrastructure development and compare the TCOs in each scenario. Lastly, we look toward 2040, compare different governmental support schemes, and calculate the cost of providing these.

Our results show that the investment decision depends on the company specifications and the infrastructure development scenario. We find that energy costs are a much more significant element of uncertainty for DTs than BETs due to lower drivetrain efficiency and more variation in diesel prices compared to electricity prices. For short-haul transportation, investing in BETs is already a better choice than DTs because the TCO is lower. For companies doing a combination of short- and long-haul, i.e., mixed transportation, the investment decision depends on the company size and the level of infrastructure development. Our findings show that large companies can benefit more from BET investments than small companies in this segment. For long-haul transportation, the investment decision is mainly determined by the level of infrastructure development. In the base scenario, BETs become cost-competitive in 2032, whereas in a rapid development scenario, they become cost-competitive in 2028. For the slow development scenario, BETs are not cost-competitive until 2036. To reach the rapid development scenario, the government needs to invest in public infrastructure. This could be less costly in time than other possible support schemes.

Sammendrag

I denne masteroppgaven undersøker vi hvordan beslutningen om å investere i batterielektriske lastebiler (BETer) blir påvirket av usikkerhet knyttet til fluktuerende energipriser, synkende kapitalkostnader og utvikling av nødvendig ladeinfrastruktur. Videre ser vi på hvordan investeringsbeslutningen endrer seg over tid for ulike typer lastebilbedrifter. Deretter ser vi på hvordan staten kan fremskynde overgangen til nullutslipp i veitransporten ved å innføre nye støtteordninger og subsidiere investeringer i infrastruktur.

Vi gjør en sammenliknende analyse av totale eierskapskostnader (TCO) for BETer og dieselastebiler (DTer), der vi hovedsakelig fokuserer på investeringsårene 2023 - 2033. TCO regnes ut ved å bruke Monte Carlo simuleringer der strøm- og dieselprisene er underliggende stokastiske prosesser. En ekstra kostnad i forbindelse med lading av BETer blir brukt for å representere ulempen som mangelen på tilstrekkelig ladeinfrastruktur gir. Vi ser på tre ulike scenarioer for infrastrukturutviklingen og sammenlikner TCO i alle scenarioene. Til slutt utvider vi analysen vår med årene 2034 - 2040, og sammenlikner ulike støtteordninger fra staten og regner ut hva det vil koste å innføre disse.

Resultatene viser at investeringsbeslutningen er avhengig av både type bedrift og infrastrukturutviklingen. Vi ser at energikostnaden er et mye større usikkerhetsmoment for DTer enn for BETer grunnet lavere virkningsgrad og mer variasjon i dieselpriser enn strømpriser. For bedrifter som kun driver med korttransport er det allerede bedre å investere i en BET enn en DT fordi TCOen er lavere. For bedrifter som driver med en blanding av kort- og langtransport, avhenger investeringsbeslutningen både av størrelsen på bedriften og scenariet for infrastrukturutvikling. Resultatene viser at det er mer fordelaktig for større bedrifter å investere i en BET enn det er for små bedrifter i dette segmentet. For bedrifter som kun bedriver langtransport avhenger investeringsbeslutningen hovedsakelig av utviklingen av ladeinfrastruktur. I basisscenarioet for infrastrukturutvikling er BETer konkurransedyktige i 2032, mens i et hurtig scenario blir de konkurransedyktige i 2028. I et langsomt scenario skjer ikke dette før 2036. For å nå et hurtig scenario må staten investere i mer offentlige ladeinfrastruktur. Over tid kan dette koste mindre enn andre mulige støtteordninger.

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Abbreviations

General Terms

BNOK	Billion Norwegian kroner
GHG	Greenhouse gas
KNOK	Thousand Norwegian kroner
kW	kilowatt
kWh	kilowatt hour
MNOK	Million Norwegian kroner
NLF	Norwegian Trucking Association
NOK	Norwegian kroner
NTP	National Transport Plan
TCO	Total cost of ownership
USD	U.S. Dollar

Fuel Technologies

BET	Battery electric truck
BEV	Battery electric vehicle
DT	Diesel truck
FCET	Fuel cell electric truck
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle

Chapter 1

Introduction

In 2015, Norway signed the Paris Agreement, committing to reduce greenhouse gas (GHG) emissions to prevent a temperature increase greater than 1.5 degrees (United Nations, n.d.). In line with this agreement, the country is committed to developing a plan to cut emissions. Norwegian road traffic stands for about 18% of the nation's GHG emissions, of which about a third is from heavy-duty road transport (SSB, 2022b). Given that more than 90% of the newly registered trucks in 2022 were diesel-driven (Statens Vegvesen, 2023b), the Norwegian government is targeting GHG reductions in this sector to cut overall emissions. Within 2030, the National Transport Plan (NTP) states that half of all new trucks shall be zero-emission and for distribution of goods in the largest city centers to be completely zero-emission (Regjeringen, 2021b). A substantial amount of investments in zero-emission trucks must occur between now and then to reach this goal.

The current zero-emission truck technologies include fuel-cell electric trucks (FCETs) and battery electric trucks (BETs). Both technologies use electricity to power an electric motor, which does not emit any exhaust. Whereas BETs draw electricity from a battery, FCETs are powered by hydrogen, which is converted to electricity by a fuel cell (U.S. Department of Energy, n.d.b). However, hydrogen-driven vehicles are still in the early stages of development, and it is expected to take years until producers deliver serial-produced FCETs to the European market (Danebergs et al., 2022). BETs, on the other hand, are a more mature technology, and electric passenger cars have become popular in Norway. Therefore, this thesis focuses on investments in BETs as a way to reduce GHG emissions from the Norwegian road transport sector.

When a trucking company replaces a truck or expands its fleet, it has to decide whether to invest in a BET or a diesel truck (DT). In doing so, the company considers multiple factors, such as costs, uncertainty, and availability of infrastructure. This is the trucking company's investment problem. BETs have a higher initial investment cost than DTs, and the number of public charging stations for heavy-duty vehicles is limited. There are also a lot of political, operational, and technological uncertainties that affect the future costs of owning BETs. These factors make trucking companies hesitant to invest in this alternative technology.

Current studies on investment in BETs mainly use deterministic models to compare the technologies. A few papers include uncertainty, but these only include some of the relevant elements. Most of the research also assumes that sufficient charging infrastructure is available. Nykvist and Olsson (2021) use constant energy prices and different scenarios for battery costs to calculate the competitiveness of BETs in comparison with DTs.

Mauler et al. (2022) use scenarios for electricity and battery costs but a constant model for diesel. The total cost of ownership (TCO) is a common way to compare competing technologies and includes all costs of owning and operating a truck throughout its lifetime. When calculating the TCO, Wu et al. (2015) and Vanhaverbeke et al. (2017) use a probability distribution to represent energy prices but do not include declining battery costs. Neither of the analyses mentioned includes infrastructure uncertainty. Lajevardi et al. (2022) calculate the TCO by using infrastructure development scenarios and probability distributions to represent electricity and diesel cost. However, they are focused on the Canadian market and do not capture the differences between companies.

Multiple factors cause cost uncertainty. The operational uncertainty is caused by fluctuating electricity - and diesel prices and a lack of charging infrastructure for BETs. Political uncertainty affects the timing of charging station development and the final cost of charging and diesel. Furthermore, the initial investment cost in BETs is currently higher than DTs but is expected to decrease with the increased adoption of BETs. This makes for technological uncertainty. We investigate the effects these uncertainties have on the investment decision of trucking companies. The final investment decision depends on their risk preference and the expected costs of operating BETs and DTs. Moreover, we explore how the investment decision will change and examine which measures can facilitate a transition to zero-emission road freight. We formulate the following research questions:

How are investments in BETs affected by operational uncertainty and the development of capital costs across different transportation companies for heavy-duty road transportation?

- In what manner does the investment decision change for different transport lengths and company structures?
- How does the speed of infrastructure development affect the investment decision?
- Which economic incentives will have the largest effect on facilitating the transition to BETs?

The contributions of this thesis include i) developing a stochastic model for the investment decision for a trucking company, ii) applying this model to a detailed case study for Norway, and iii) including a thorough analysis of the potential government support schemes that can help accelerate the transition to BETs. We focus on the period from 2023 to 2033 and compare the TCOs for a BET and a DT each year using Monte Carlo simulations. We consider three scenarios for infrastructure build-out and include an intangible cost related to refueling inconvenience for BETs, similar to prior work by Lajevardi et al. (2022). We expand this research by letting refueling inconvenience depend on the transport distance and company size. We further adjust the model to the Norwegian market by using data from a survey sent out to the members of the Norwegian Trucking Association (NLF). The result is a model where the optimal investment decision for a company depends on the scenario for infrastructure development, company size, and daily transport length, which can be directly used by trucking companies. Lastly, we compare the costs of implementing various support schemes to determine the most effective governmental measures.

The thesis begins with an overview of the heavy-duty transport market in Norway and describes relevant costs and uncertain elements in Chapter 2. Next, we explore the related literature in Chapter 3. Chapter 4 presents the methodology, and Chapter 5 describes the data input to our model. Chapter 6 presents our findings which are discussed in Chapter 7. We conclude and discuss areas for further research in Chapter 8.

Chapter 2

Background

This chapter provides the background for our research questions and the trucking company's investment problem. First, an overview of heavy-duty road transportation in Norway is presented in Section 2.1. In this section, we examine the market, political landscape, and developments in the industry. Next, we describe truck designs in Section 2.2 and discuss the necessary infrastructure for BETs in Section 2.3. Section 2.4 describes the cost structure of trucking companies and explains the various cost components involved. Section 2.5 elaborates on the role of uncertainty for investments in BETs as an alternative fuel technology. Finally, Section 2.6 outlines the specifications relevant to the Norwegian road transport market.

2.1 Heavy Duty Transportation in Norway

This section describes the existing market and explains ways to segment heavy-duty road transportation in Norway. It then presents the political landscape, focusing on existing regulations and incentives. Lastly, it reports the main developments towards BETs in the industry.

2.1.1 Market

In 2022, the Norwegian transport market consisted of around 70 000 trucks responsible for transporting 261.9 million tons of goods (SSB, 2023a,b). The market is fragmented, with multiple actors spanning large geographical areas (Oslo Economics, 2015). In general, the market is dominated by small and medium-sized businesses. NLF represents around 20 000 trucks, which is somewhat less than a third of the market (NLF, 2022a). Out of NLF's members, 76% have ten or fewer trucks in daily operation, 60% have five or fewer trucks, and 37% are independent one-truck owners (NLF, 2022c). We assume this ownership structure represents the entire road freight market in Norway.

The road freight market can be divided into five main segments, depending on the type of goods transported (SSB, 2022e). These are:

1. Agricultural, forestry, and fishing products (13.2%)
2. Food products, beverages, tobacco, and animal fodder (22.0%)

3. Coal, oil and chemical products (10.9%)
4. Metal ores, stone, sand, gravel, clay, salt, cement, lime, and other manufactured construction materials and waste (26.1%)
5. Other manufactured goods and grouped goods (27.7%).

The amount of transport work conducted in 2021 is expressed in percentages, which is the number of tons transported multiplied by the average distance traveled. This measure is more representative than weight alone since heavier goods such as sand and gravel are usually transported shorter distances.

Trucks are typically classified by their weight (T. Foss & D. Nordvik, personal communication, 19.09.2022), with the maximum allowed total weight for trucks in Norway being 60 tons for a 24-meter truck (Stølen, 2020). The U.S. Department of Energy (n.d.d) classifies trucks heavier than 12 tons as heavy-duty vehicles, and this is used consistently throughout the industry. Furthermore, there is a difference between the daily transport distances done by trucking companies. NLF (2022b) defines local transportation as transport with a 50 km range, regional transportation with a 100 km range, and long transport with around 500 km range. A general rule is that local transportation means multiple trips during the day, regional transportation is one return trip, and national transportation means the driver returns the next day. However, the definitions of local and regional transportation may vary depending on location. For example, in more remote areas with longer distances, such as northern Norway, a driving range of 100 km could be defined as local transportation (T. Foss, personal communication, 03.03.23).

2.1.2 Political Landscape

In 2022, 92% of all newly registered trucks were DTs, whereas 8% were classified as zero-emission trucks (Statens Vegvesen, 2023b). This is an apparent increase from 2021 when only 1% of trucks were zero-emission. All of these newly registered zero-emission trucks in 2021 and 2022 were BETs. To give zero-emission vehicles an advantage, several existing regulations differentiate between vehicle technology:

- Depending on the toll station, zero-emission vehicles get a 50-100% toll discount (Autopass, 2023). On ferries, the discount is 50% (Statens Vegvesen, 2023a).
- Zero-emission vehicles can use the public transportation lane if they contain at least two passengers during rush hour (Statens Vegvesen, 2021).
- Zero-emission vehicles are exempted from both the road use tax and the CO_2 tax (Regjeringen, 2022b) since these are incorporated into the fuel price.
- All truck owners have to pay a weight-based fee, which includes an environmentally differentiated component for diesel-driven vehicles(Skatteetaten, 2023).
- The government provides a 40% grant for the extra additional investment that is needed for BETs compared to DTs (Enova, 2021).

In 2019, the municipality in Oslo decided that all public deliveries must be done in either zero-emission or biogas-driven vehicles by 2025 (DFØ, 2022). In current competitive tenders, the municipality favors these technologies. Oslo, therefore, has a significantly higher share of BETs than other cities, with 16% of new trucks being electric in mid-2022 (Barbøl, 2022). In 2022, the city also became a pilot city for zero-emission heavy-duty transport. In late 2022, Bergen, Stavanger, and Trondheim stated that they would follow through with the same demands as Oslo (Hauge et al., 2022). These four large cities are urging the government and private actors to make similar demands to facilitate the transition to zero-emission road transport.

2.1.3 Developments in the Industry

The trucking companies that have already invested in BETs are typically large companies that can combine different fuel technologies in their fleet. A mixed fleet provides more flexibility because the company can change between different vehicles if one technology is unsuitable for an assignment. Additionally, large companies can invest in charging infrastructure at their own depots that can be used by several vehicles.

The Norwegian parcel service (Posten Norge) bought its first BET in 2021, which had a maximum weight of 26 tons and a 264 kW electrical motor (Nesheim, 2021). In 2022, they announced that they ordered 50 more BETs, which will soon be seen on Norwegian roads (Reiersen, 2022). ASKO, the largest grocery wholesaler in Norway, bought 40 new BETs for their central warehouse in Vestby in 2022 and plans to increase this number to 126 within 2026 (Spaun, 2022). They are also investing in charging infrastructure in collaboration with ABB E-Mobility, which is supposed to be finished within the first quarter of 2023. This includes 58 charging spots with a 90-350 kW capacity located at their distribution warehouse. Additionally, ASKO has invested in one large BET with a battery pack of 900 kWh that can drive 500 km without charging, which arrived in late 2022 (NorgesGruppen, 2022). When using high-speed charging of 350 kW, it takes 1 hour and 40 minutes to charge it from 20% to 80%. This is the first of its kind in Northern Europe and will be used for long-haul transport between central locations in Norway. Felleskjøpet, the largest cooperation enterprise for agriculture in Norway, have also recently bought a BET in collaboration with their transporter. This is going to be used to transport animal fodder in Central Norway (Bye, 2023). The truck has a battery of 540 kWh and will be charged every night. They have also made an agreement with the Municipality of Trondheim to use the municipality's fast charger when making day trips to the city.

2.2 Truck Technology

Figure 2.1 shows the main components of a truck. Truck owners usually divide the truck into two parts: the body and the chassis (T. Foss & D. Nordvik, personal communication, 19.09.2022). The truck body contains the cargo and sits on top of the chassis (Law Insider, n.d.). This part has a specific design depending on the type of goods to be transferred (T. Foss & D. Nordvik, personal communication, 19.09.2022). The chassis consists of the frame, the cab, and the powertrain. The cab is where the driver is seated and is usually the same, independent of technology and goods to be transported. The frame is the main support structure of the vehicle where the other components are connected (Stevens, 2016). Lastly, the powertrain converts the engine's power into movement (Stevens, 2016) and is the component where DTs and BETs differ the most. For both BETs and DTs, the powertrain contains a transmission, driveshaft, axles, and wheels.

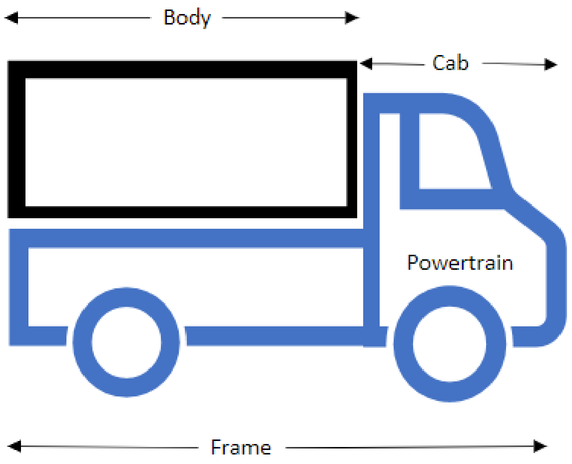


Figure 2.1: Main components of a truck. The blue color indicates the chassis, which consists of the frame, cab, and powertrain.

In BETs, essential powertrain elements are an electric motor, an inverter, a converter, a charger, and a battery pack (Johnson, 2014). The transmission in BETs is much simpler than for DTs. As opposed to DTs, BETs do not use internal combustion engines (ICE). Instead, the battery pack powers the electric motor (U.S. Department of Energy, 2022). The most common battery packs for BETs use lithium-ion cells as the energy carrier. As a reference, Volvo's BETs can contain up to 6 battery packs, each storing about 90 kWh of energy, giving a total battery capacity of 540 kWh (O'Leary, 2022). However, the battery's full capacity is not used when driving, which is done to maintain the battery's health (Klingenberg, 2022). Volvo recently tested their FH Electric truck with a 540 kWh battery on a mixed route in Germany. With a consumption of 1.1 kWh/km, the truck had a reported range of 345 km (Volvo, 2022), which gives an available battery size of around 380 kWh. The driving range will also vary with the loads on the truck.

A DT powertrain contains more moving parts than an electric powertrain (Interplex, n.d.) and uses an ICE running on diesel (U.S. Department of Energy, n.d.a). ICEs have lower efficiency, defined as the ratio between power output and input, than electric motors. For diesel vehicles, the efficiency is 30-45%, while for electric vehicles, it is 70-90% (Wikse, 2022).

2.3 Charging Infrastructure

The batteries of BETs are charged with electricity using alternating current (AC) or direct current (DC) chargers. The difference between AC and DC chargers lies in the location in which the AC power gets converted to DC. While a DC charger converts AC to DC inside the charger itself, this conversion happens inside the vehicle when using an AC charger (Wallbox, n.d.). Additionally, DC chargers provide a higher power (in kW) than AC chargers. Charging time until fully charged increases with higher battery capacity (in kWh) and with lower power of the charger (Engdahl, 2021). Generally, AC chargers are located at depots or at home, where trucks charge overnight. In contrast, DC chargers are situated in charging stations where trucks charge for a shorter time during their transport mission. When the battery reaches 80 %, the charging time increases (Fjordkraft, n.d.). According to Engdahl (2021), when using an AC onboard charger (43 kW), it will take around 10 hours to go from an empty battery to fully charged, while this can take about 2 hours when using a DC charger (max 250 kW). The charging time also depends on the battery size in kWh and therefore varies depending on the specific type of truck. For instance, a regional transport truck from Scania with a driving range of up to 350 km and 40 tons GVW (Gross Vehicle Weight) is fully charged within 90 minutes with a DC charger of 370 kW (Scania, n.d.).

In Norway, more than 5000 public high-speed chargers are available for battery electric passenger cars (Norsk Elbilforening, 2022). However, this is not the case for BETs. Although the charging technology is similar, some differences make the current high-speed chargers unsuitable for BETs. For example, trucks require more space and a higher voltage (Broback, 2021). There is currently only one public charging station for heavy-duty trucks, located in Filipstad in Oslo (Pau, 2022). This is a 184 kW charger operated by Kople and has the same price per kWh as electric cars have in regular charging stations. Additionally, the Municipality of Oslo has released a new support scheme, in which they grant 80% of costs related to establishing new public charging stations around the city (Oslo Kommune, 2022). During the first application round in December 2022, funding was granted to 28 chargers in 4 different locations (KlimaOslo, 2023a). In the second application round in March 2023, funding was granted to 27 chargers in 3 locations (KlimaOslo, 2023b). The total support for the 55 chargers is around 50 MNOK and the build-out is expected to be completed before summer 2024. Additionally, Enova has released a new support scheme for trucking companies that want to invest in chargers for their own use (Enova, 2022). In this case, companies can get 40% of the investment cost granted.

According to Afshar et al. (2021), existing charging methods for electric vehicles can be classified into fixed charging stations, mobile charging stations, or contactless charging stations. Fixed charging stations include public and private charging stations and are the most common way of charging electric cars in Norway. These are directly connected to the power grid or a local energy generator. Mobile charging stations include portable charging stations, truck mobile charging stations, and vehicle-to-vehicle power transfers. The benefit of mobile charging stations is that they can be temporarily placed in various locations to find optimal placement. This can be a short-term solution to speed up the transition to zero-emission road freight. Lastly, contactless charging stations do not require the electric vehicle to be directly connected to the power supply. This includes wireless charging, in which vehicles are charged through a magnetic connection while on the road, and battery swapping, in which the battery pack is replaced with a fully charged one. Battery swapping is something that China is investing heavily in, both for passenger cars and trucks (Lienert et al., 2022). This industry is expected to grow a lot in the country in the coming years (Yukun, 2023). Another option is catenary charging, in which the vehicle is charged through an overhead wire. However, this will require a significant infrastructure build-out and is not considered cost-effective for the Norwegian market (Danebergs et al., 2022).

There are several challenges regarding infrastructure development, both in general and specific to Norway. First, building out a network of accessible charging stations that covers the entire country is costly. In Sweden, the government has granted total funding for building 139 charging stations and 12 hydrogen filling stations all over the country (Energimyndigheten, 2022). These are expected to be finished during autumn 2023, and the project's estimated cost is 1.4 billion SEK. Second, significant power grid investments will be necessary to handle the increased demand for electricity (Sintef, 2022). Especially if fast charging is enabled, the existing grid is unable to handle the increased power. Third, if the necessary infrastructure is actually built out, the problem of queues at charging stations may arise. After driving for 4.5 hours, truck drivers are required to have a 45 minutes rest (Statens Vegvesen, n.d.), which can be used to charge the BET. However, truck drivers will potentially stop at the same charging stations. This could result in an extra waiting time at the charging facility, which means a monetary loss for the trucking company. It will also put a higher demand on the power grid in these locations.

2.4 Costs

In this section, we look into the costs of owning and operating BETs and DTs. The heavy-duty transport sector is an industry with low margins where more than half of the trucking companies have an operating margin of less than 5% (NLF, 2019). Costs are, therefore, a decisive factor when choosing which trucking technology to invest in. The TCO considers all relevant costs of owning a truck during its operational period and can be split into capital and operational costs. Operational costs are further grouped into energy costs and other operating costs. This is shown in Figure 2.2.

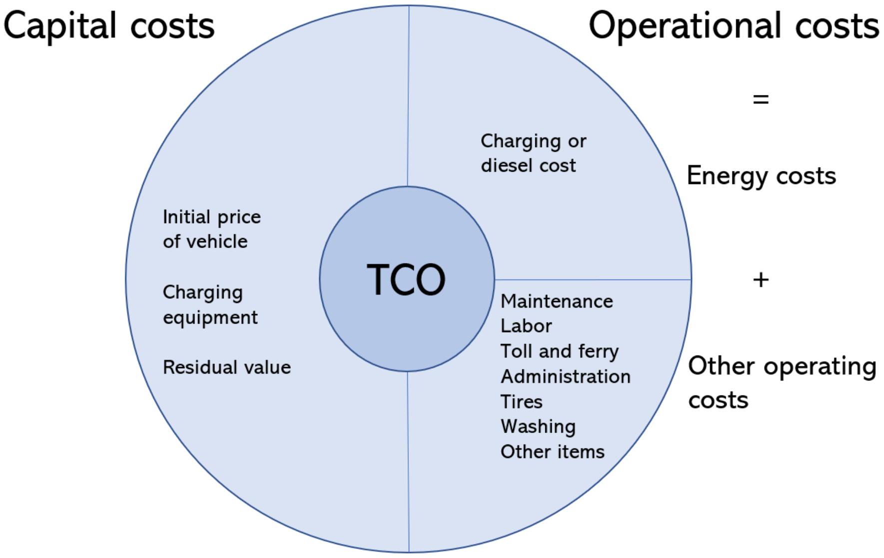


Figure 2.2: Overview of cost components included in the TCO.

2.4.1 Capital Costs

The capital cost of a BET or a DT is the initial purchase price minus the residual value. An eventual investment in charging equipment is also a capital cost for the trucking company. According to Figenbaum et al. (2019), the initial investment in a BET was around 230 - 250% of a similar DT in 2019. The battery pack causes a significant amount of the cost difference between DTs and BETs. Phadke et al. (2021) estimate capital costs for BETs to decline, primarily based on a projected battery cost decrease from \$135/kWh in 2020 to \$60/kWh in 2030. According to an annual battery price survey from BloombergNEF (2022), battery costs have decreased yearly from 2013 to 2021. However, prices rose between 2021 and 2022. For battery electric vehicles (BEVs) specifically, the volume-weighted average basis price was \$138/kWh in 2022 (BloombergNEF, 2022), up from \$118/kWh in 2021 (BloombergNEF, 2021).

Trucks are usually resold after 5-7 years, often to other countries (T. Foss & D. Nordvik, personal communication, 19.09.2022). For DTs, 20% of the purchase price is commonly used as residual value (Stølen, 2019). Predicting the residual value of BETs is challenging due to the limited availability of used electric trucks in the market. The future residual value will be affected by the development of the charging infrastructure as a more extensive network expands the truck's suitability for various routes. Additionally, the development of battery technology will affect the residual value. If the batteries produced in the future are significantly better in range, then the residual value might be lower. The availability and lead time on new trucks and the future initial investment price will also affect the worth of a used BET.

2.4.2 Operational Costs

Operational costs consist of energy costs and other operational costs, where energy costs are either charging or diesel costs. Other operational costs comprise additional costs that occur when operating the truck, such as maintenance, labor, toll, and ferry costs (NLF, 2022b).

Charging Cost

The charging cost is the cost of charging at public charging stations, charging depots, or using at-home chargers. Figure 2.3 shows the cost components included in the charging price.

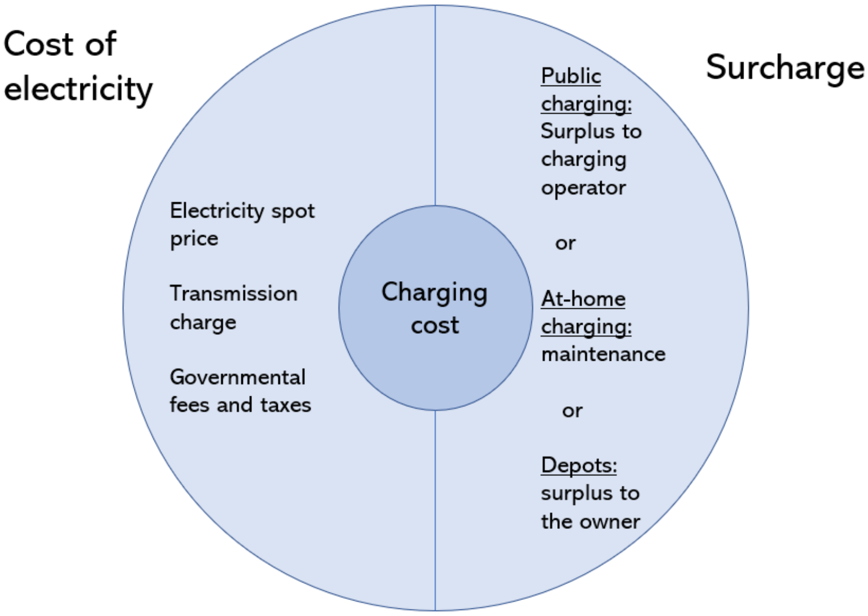


Figure 2.3: Overview of the charging cost components.

Three components determine the cost of electricity; the electricity price, transmission charge, and government fees and taxes (Lyse, 2022). The electricity price is the amount paid to the electricity provider and depends on the consumption. The price per kWh is either the spot price, which is the market price for electricity, or a fixed price agreed upon. A third option is a variable price contract, which is a mix of the other two. The spot price varies hourly, while a fixed price agreement usually lasts 6 months to three years (Elskling, 2023). The spot price is variable and is affected by external factors such as demand for coal and gas or the weather (Statnett, 2022b). The electricity price also varies depending on the electricity price zone. Norway is divided into five zones, NO1 (Eastern Norway), NO2 (Southern Norway), NO3 (Mid-Norway), NO4 (Northern Norway), and NO5 (Western Norway). The division into electricity price zones is shown in Figure 2.4. The reason for the division is that the power system is weather dependent, and there is not enough capacity in the power grid to even out the supply differences between the regions (Statnett, 2022a). This gives an electricity price that varies depending on the region.

Figure 2.4: Electricity price zones in Norway.

Through Nord Pool, Norway is part of the European power market, so international events will also affect the electricity price. The transmission charge refers to the payment made to the power grid operator for the transportation of electricity (Tensio, 2023). The cost varies for private customers and businesses, and it further relies on the company's size and electricity consumption level. Lastly, governmental taxes include an electricity usage fee, Enova fee, and VAT (Statnett, 2022b). The governmental taxes are usually included in the price paid to the power grid operator. Furthermore, trucking companies using electricity to power the vehicle can usually omit VAT from the calculation because it is transferred to customers as outgoing VAT (Altinn, 2022).

For public charging, the charging cost is higher than the actual electricity cost. This is because the stations add a surcharge to cover investment costs and operational costs at the charging location. Moreover, the stations will likely add a provision to the surcharge. As of March 2023, Kople charges between 7.49 and 8.49 NOK/kWh for high-speed charging, depending on the electricity pricing zone (Kople, 2023). With the current electricity prices, the surcharge lies between 5 and 7 NOK/kWh.

Diesel Cost

Three main components determine the Norwegian diesel price; the international diesel price, taxes, and gross profit for the petrol station companies (Drivkraft Norge, 2019), as shown in Figure 2.5. A general rule is that these usually are 60%, 30%, and 10% of the final pump price, respectively.

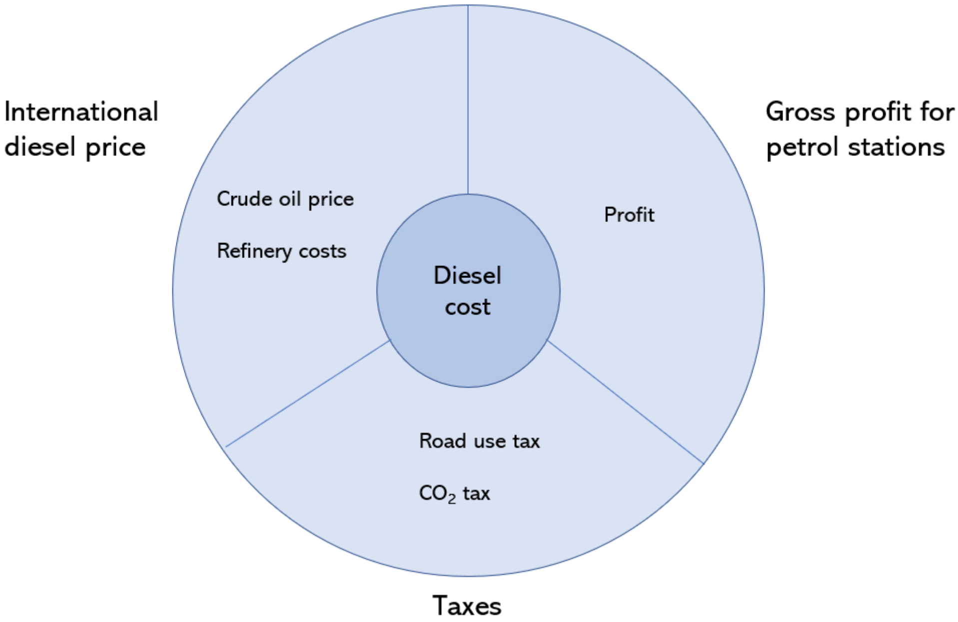


Figure 2.5: Overview of the diesel cost components.

Various factors influence the international diesel price, such as currency fluctuations, refinery costs, and supply and demand for crude oil (Korlyuk et al., 2015). The international diesel price can be seen as the crude oil price plus the refinery costs. According to (EIA, 2022), the crude oil price accounted for 50% of the monthly average diesel price in the US from 2000 to 2021. The relevant taxes for the Norwegian diesel price are the road use tax, the CO_2 tax, and VAT. In 2023, the road use tax is 2.92 NOK/liter, and the CO_2 tax is 2.53 NOK/liter (Regjeringen, 2022b). In 2021, the government proposed in their climate plan that the CO_2 tax should increase by 15% each year until 2030 (Rustad, 2021). From 2021 to 2022, the tax actually increased by 30%, and from 2022 to 2023, it increased by 23% (Regjeringen, 2022a). VAT is usually 25% of the final pump price but can be omitted for the same reason as described for the electricity price.

Other Operational Costs

Other operational costs are labor, toll, ferry, administration, maintenance, tires, washing, and other items (NLF, 2022b). Maintenance, toll, and ferry costs are the elements with the most significant cost difference between DTs and BETs. According to (U.S. Department of Energy, n.d.c), BEVs generally require less maintenance than conventional vehicles for four reasons. First, the motor, battery, and associated electronics require minimal maintenance. Second, there are fewer liquids, such as engine oil, that require regular maintenance. Third, due to the regenerative braking of BEVs, brake wear is significantly reduced. Lastly, BEVs have fewer moving parts than vehicles with ICEs. These factors combined make the maintenance costs significantly lower for BETs than DTs. Toll and ferry costs are lower due to the political incentives discussed in Section 2.1.

2.5 Uncertainty

The uncertainties regarding BETs can be categorized into political, technological, and operational uncertainty. Figure 2.6 shows an overview of the main identified elements. This section discusses these in more detail.

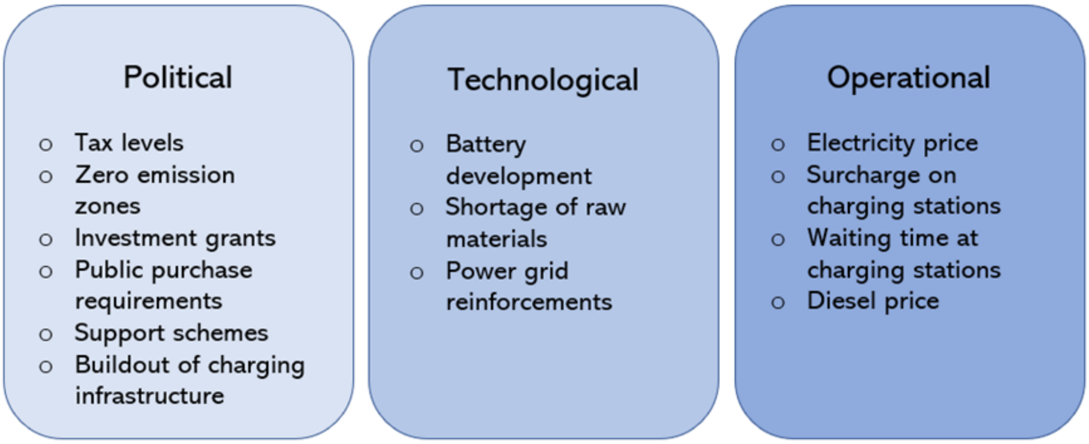


Figure 2.6: Classification of uncertainty elements.

2.5.1 Political Uncertainty

Political uncertainty relates to regulations and policies in terms of which measures will be introduced and which will be removed. EU has a goal of becoming climate neutral by 2050 (Regjeringen, 2021a), and to reach this goal emitting CO_2 will become more expensive. The tax level on fuel is subject to yearly changes, but it is difficult to know how much it will change. So far, the annual increase in the CO_2 tax has been greater than initially proposed in 2021. Furthermore, there is a possibility of changes in the existing regulations and incentives. Today, electric vehicles can only use the public transportation lane during rush hour if they have at least one other passenger (Statens Vegvesen, 2021). Since truck drivers are usually alone in the car, exempting them from the requirement of needing an extra passenger could pose an advantage. It has also been a much-discussed topic whether Oslo and Bergen should have zero-emission zones in the city center, in which vehicles emitting CO_2 is not allowed. However, as of January 2023, the government refused this proposal, and the next possible adoption is not until 2025 (NTB, 2023). The refusal is despite the willingness of the Municipality of Oslo. When it comes to supporting schemes, there is also uncertainty. Today the government, through Enova, grants 40% of the additional investment cost in zero-emission trucks compared to DTs, but this can be subject to changes in the future. When assuming the charging infrastructure is present, our project thesis showed that if the government grants 100% of the additional investment cost compared to a DT, BETs are the cheaper option (Krüger & Thiis, 2022).

Our project thesis also showed that the presence of charging infrastructure is necessary for trucking companies to invest in BETs (Krüger & Thiis, 2022). If trucking companies cannot drive specific routes because of lacking infrastructure, they lose the flexibility that DTs provide. This implies further uncertainty and monetary losses for the company. If infrastructure is sufficient, there is less uncertainty related to BETs than DTs, but this is not yet the case. At some point in time, this is most likely built out, but the timing largely depends on political decisions about investment grants and power grid reinforcement.

2.5.2 Technological Uncertainty

The technological uncertainty is mainly related to battery development and power grid reinforcements. As mentioned, battery costs have decreased yearly from 2013 to 2021 but risen again from 2021 to 2022. However, as the world gets electrified, the demand for batteries increases, and battery prices might rise. Combined with a shortage of necessary raw materials like lithium, research firm E-Source estimate that battery costs for EVs might rise by 22% until 2026 (LeBeau, 2022). After that, they estimate that prices will decline. Improvements to the current power grid are necessary to handle charging during peak demand times (Sintef, 2022). It is currently unknown when such reinforcement will be in place, and the lack of such reinforcement can cause delays in infrastructure development.

2.5.3 Operational Uncertainty

Both the electricity and diesel prices are operational uncertainties that are affected by macroeconomic factors that are difficult to predict. Additionally, the electricity price is weather dependent, which contributes to price variations. In our project thesis, we modeled electricity and diesel prices as stochastic elements to evaluate how variations in these affected operational costs for BETs and DTs (Krüger & Thiis, 2022). For BETs, we discovered that the surcharge for charging at public charging stations, rather than the electricity price, had the most significant impact on the TCO, although the electricity price showed more variability. On the other hand, diesel price uncertainty is mainly caused by crude oil price variations, which is a larger part of the final diesel price. Moreover, the possibility of queues at charging stations once built out can be seen as an operational uncertainty. Time spent waiting in line means additional costs for the trucking company, and a queuing system that minimizes the time spent at charging facilities should be introduced.

2.6 Specifics of Norway

Every year NLF sends a conjuncture survey about the industry to their members. The questions include information about the trucking companies, such as location, number of trucks, type of goods transported, contract length, and whether they do local, regional, or national transportation. Most of the questions have the option to select multiple alternatives. In 2022, NLF received 526 replies, which is about 20% of their members. Through NLF, we sent an additional survey to the members who responded to the conjuncture survey, asking about their operational patterns. We received 268 responses, which is a 50% response rate. This is about 10% of the NLF's members. We then matched the answers with the conjuncture survey to gain more information about the respondents. The results can be found in Appendix A. This section discusses the main findings from the survey.

2.6.1 Costs

As discussed in Section 2.3, there is a risk of queues at public charging stations. We, therefore, asked the respondents to state the hourly cost in NOK for the company if the transport was delayed. The results show that of the respondents, around 45% do not know the time value of delays, 5% do not wish to state it, and the remaining 50% do have an estimate. The answers varied, but the majority of those who stated a value selected the range 751 - 1000 NOK/hour. The remaining respondents selected intervals that were practically normally distributed around this interval. To the respondents that stated a value, we further asked which costs they included in their answer, and the results varied. The respondent that stated that they paid less than 250 NOK only included a fee for late delivery. The respondents that stated that they paid 251 - 500 NOK/hour mainly included salary costs. For the remaining options, the respondents generally included salary costs, lost revenue, and fixed and variable costs. Some respondents also stated that they chose the interval that included their hourly rate. Only a few stated that the cost included a fee to the transport buyer.

We see two possible explanations for the observed price variations. 1) The companies selecting the lower cost intervals only included increased salary or overtime payments and forgot to include other costs that occur. If this is the case, the responses will not represent the actual situation. 2) The monetary value of time is different across companies. The observed differences could be because some types of goods are more time-critical than others. It can also be related to company size and the number of trucks and drivers available to cover the following assignments.

Some TCO analyses, such as Gjerset (2022), show that BETs could be cheaper than DTs when assuming that sufficient infrastructure exists. We, therefore, asked how the companies make investment decisions and whether they use any decision tools. The results showed that 69% do not use any decision tool, 25% use TCO calculation, and 6% use other tools. Other tools were typically specified as personal calculations and accounting. These results show that a third of the companies use economic decision tools when deciding which vehicle to invest in. This highlights the importance of showing the potential economic advantages of BETs or other alternative fuel technologies.

2.6.2 Truck Parking

As discussed in Section 2.4.2, public charging is typically more expensive than using company-owned chargers due to a surcharge set by the charging operator. We asked the companies where their trucks were parked during the night. The respondents could select multiple alternatives and state how many cars were parked in each location. 84% of the respondents selected multiple locations, and 2 526 trucks were located. The results showed that 54% of the trucks were parked at the company property or at home with the driver. Furthermore, 33% were parked at depots, terminals, loading- and unloading areas, 24-hour rest stops, or at the customer's location. Of the remaining trucks, 3% were parked in other places, while 10% were used during the night. If we assume that trucks can fully charge overnight, these responses show that charging overnight with company-owned chargers, either at the company property or at home with the driver, applies to more than half of the trucks. The other trucks not used at night would require overnight public charging.

2.6.3 Variation and Flexibility

For most trucking companies to invest in BETs, charging stations must be available. Furthermore, the charging stations must be strategically placed in central locations along main transport routes and large cities. This placement depends on the driving patterns of the trucking companies and whether they have variable or fixed routes. The respondents were therefore asked to state on a scale from 1 to 5 how variable vs. fixed their routes are, where 1 = *only fixed* and 5 = *a lot of variation*. The results show that most companies have large variations in routes, with 39% having a lot of variation and 7% having only fixed routes. The remaining 53% of respondents did a combination of fixed and varied routes.

If there is no available charging station in an area, the company might have to reject assignment offers due to a lack of accessibility. The flexibility of varying routes could, therefore, be an important argument against investing in BETs before a complete infrastructure is built out. We, therefore, asked the trucking companies to state how important flexibility is on a scale from 1 to 5, where 1 = *not important* and 5 = *very important*. Flexibility were defined as the possibility to drive both short and long distances in addition to various routes. The responses show that flexibility is very important for most companies, with 59% stating that flexibility is very important and only 4% saying that it is not important.

When aggregating based on company size, i.e., the number of trucks that the company has at its disposal, there is a decreasing trend of how variable routes are and how important flexibility is. Figure 2.7 shows the percentage of respondents in each company size group that answered 5 for variability and 5 for the importance of flexibility. The results show that as the number of trucks increases, the company drives more fixed routes. Half of the companies with 1 or 2 trucks state that they have very variable routes, whereas for the companies with 21-200 trucks, only 20% state that they have very variable routes. This could be because companies with many trucks have more possibilities to have some fixed assignments and take on additional ones. As for the importance of flexibility, there is a decreasing trend in importance for companies with ten cars or more. This means that flexibility is more important if the company is small.

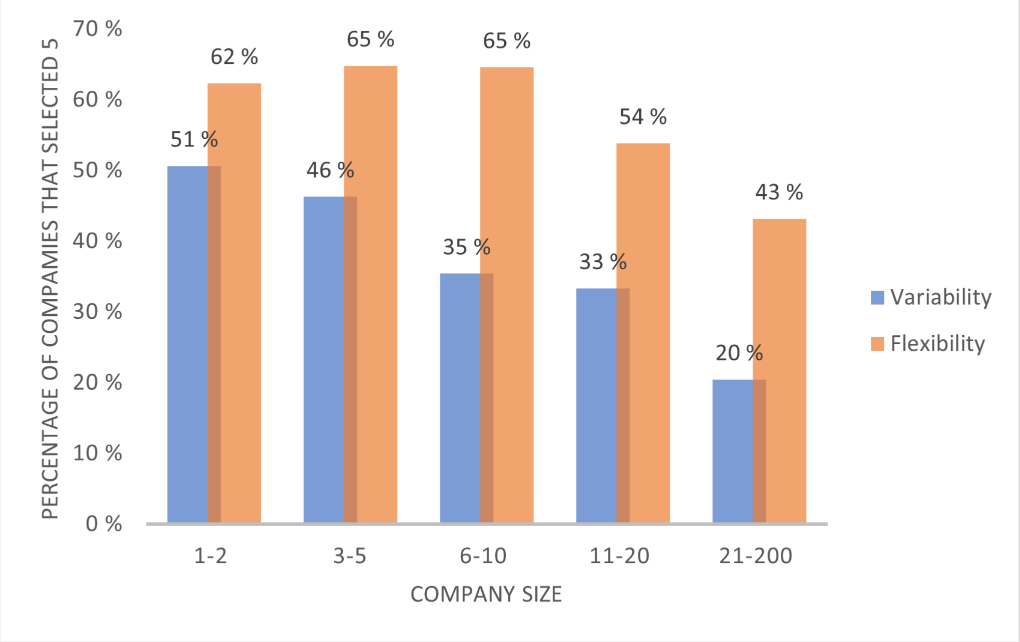


Figure 2.7: Percentage of companies with a specified size that answered 5 for variability in routes (very variable) and 5 for the importance of flexibility (very important).

Chapter 3

Literature Review

This chapter presents an overview of the relevant literature on investments in BETs and uncertainty. First, in Section 3.1, we describe our literature search strategy. Next, in Section 3.2, we present literature about the investment decision, focusing on TCO analyses. Then, in Section 3.3, we explore different options for handling uncertainty when estimating the TCO for BETs and BEVs. This section includes some studies on other vehicle types, as the literature assessing TCOs for BETs under uncertainty is sparse. In Section 3.4, we explore options for estimating capital costs, infrastructure costs- and uncertainty, and energy costs. Section 3.5 describes how stock flows models can be used to project the fleet composition. In Section 3.6, we study the discount rate in the transport sector. Lastly, we summarize the reviewed literature in Section 3.7 and present the research gap and our contributions in Section 3.8.

3.1 Literature Search Strategy

Our literature search strategy consists of using relevant search words on Google Scholar and Scopus. Our primary search terms include *battery-electric truck* and *battery-electric vehicle*, which we combined with other relevant terms such as *uncertainty*, *charging*, and *infrastructure*. We include papers that specifically look into investments in BETs, in addition to costs and challenges related to infrastructure development. Since the BET market is still in its infancy, we also explore the literature on the electric passenger car market. Moreover, we study literature on electricity and diesel price forecasting to use for future cost estimations.

3.2 Truck Investment Models

One way to determine which technology to invest in is by using fleet replacement. These problems find an optimal replacement schedule that minimizes the cost of operating and owning the vehicle. Alp et al. (2022) show that a cost-minimizing plan which includes BETs in the truck fleet can be developed by using fleet replacement. Parthanadee et al. (2012) create vehicle replacement rules by considering alternative fuels and user preferences. However, fleet replacement problems are usually quite complex. We want to create a general model that can be used directly by different types of trucking companies. Fleet replacement is not suitable for this purpose, so we therefore focus on TCO analyses. These can directly answer the trucking company's investment problem.

TCO analysis can be used to compare the lifetime costs of owning a BET with a DT. Figenbaum et al. (2019), Gray et al. (2022), Lajevardi et al. (2022), Mauler et al. (2022), Noll et al. (2022), Nykvist and Olsson (2021), and Phadke et al. (2021) use TCO analysis to evaluate investment decisions in BETs. The results of the recent TCO analyses show that lifetime costs for BETs are getting closer to or even falling below that of DTs. Mauler et al. (2022) find that BETs are close to competitive with DTs for ranges below 500 km. Gray et al. (2022) find that BETs have lower TCO than DTs for ranges below 450 km for electricity costs lower than 100 euro/MWh. Phadke et al. (2021) find that the TCO for BETs is less than for DTs for daily driving distances of 480 km and 640 km. However, they emphasize that BETs have higher upfront costs due to their higher capital costs compared to DTs. Noll et al. (2022) use TCO analysis to compare the competitiveness of zero-carbon road-freight technologies with fossil fuels for different weight segments in ten European countries. When categorizing trucks by weight, Noll et al. (2022) find that especially for light and medium weight segments, BETs are close to competitive with DTs. Figenbaum et al. (2019) compare TCO for DTs, BETs, and FCETs in 2019, 2025, and 2030. They estimate that the TCO for BETs is about 50% more expensive than DTs in 2019, and by 2025 the TCO for the two technologies will be about the same. Further, they estimate that BETs will be the cheaper option in 2030. Nykvist and Olsson (2021) find that BETs are competitive to DTs in an optimistic battery cost scenario, where battery costs are 100 USD/kWh. However, they assume 1MW chargers are available, which is currently not the case. Lajevardi et al. (2022) find that BETs are not yet competitive with DTs due to high battery costs and costs of fast charging stations. Overall, the literature search shows that the differences in cost competitiveness for BETs and DTs mainly rely on the assumptions used for charging infrastructure, fuel costs, and capital costs.

3.3 Handling Uncertainties

The choice of input parameters in the TCO estimations varies among the reviewed literature, leading to differences in the results. Uncertain parameters, such as electricity and diesel prices, further contribute to this variation. To address this uncertainty, different strategies are employed in the TCO calculations. These include Monte Carlo analysis, scenarios, and sensitivity analysis.

3.3.1 Monte Carlo Analysis

Monte Carlo analysis is a common way to handle investment uncertainties and is used to account for multiple stochastic elements when comparing the costs of BEVs with other fuel technologies. This is done by Gray et al. (2022), Hao et al. (2020), Lajevardi et al. (2022), Noll et al. (2022), Vanhaverbeke et al. (2017), and Wu et al. (2015). For a TCO analysis on BETs, the stochastic elements may include fuel prices or other operational cost components, capital costs, or charging technology. A probabilistic Monte Carlo simulation is performed by Noll et al. (2022), where the PERT and normal distributions are used for CAPEX components and fuel prices, respectively. Hao et al. (2020) look into the passenger car market in China and use Monte Carlo analysis to compare the TCO of BEVs with that of plug-in hybrid electric vehicles and internal combustion engine vehicles (ICEVs). For energy prices, they project the gas price based on Brent crude oil price projections from the U.S. Energy Information Administration and fit the retail gas price to the triangular distribution, while the electricity price is assumed constant. Furthermore, the daily driving distance is represented by a gamma distribution. The inconvenience of time spent charging is represented by a time price value randomly distributed between the highest and lowest hourly wage for each city. Moreover, they deploy a cost of alternative transportation for cases when BEVs have an insufficient range and other transport forms are needed. Wu et al. (2015) compare TCOs of BEVs and ICEVs in the passenger car market, where they model future operational and capital costs as stochastic elements using the PERT distribution. Inputs for maximum, minimum, and most likely values to the distributions are the projected yearly changes in percentage. In Gray et al. (2022), the uniform and the triangular distributions are used for capital cost components. They also use different cost levels per MWh for overnight charging and fast charging and incorporate a fee to the station owner in the estimated charging costs. This charging cost is added to the TCO in a variable called Total System Cost. Lajevardi et al. (2022) simulate competition among multiple types of drivetrain technologies under different infrastructure conditions for long-haul and short-haul driving. They use price variations for various components in capital cost estimations and the assumed refueling time. Vanhaverbeke et al. (2017) use Monte Carlo analysis to compare TCO for battery electric passenger cars to cars with internal combustion engines and consider energy prices and different vehicle-to-grid conditions as stochastic elements.

3.3.2 Scenarios and Sensitivity Analysis

According to Mietzner and Reger (2005), scenarios are a set of stories describing various possibilities in the future. These stories provide a picture of the future state of the world under different conditions and can help guide decisions about BET investments when facing uncertainty. Mauler et al. (2022) look at how different scenarios for technology development and energy prices affect the cost of owning BETs compared to FCETs and DTs. Nykvist and Olsson (2021) use three scenarios for battery costs, lifetime, and power density to explore how battery specifications affect the TCO. Lajevardi et al. (2022) explore how different scenarios for infrastructure development affect the TCO. Hao et al. (2020) explore a more optimistic and a less optimistic scenario for BEV cost development in addition to their base scenarios. The optimistic scenario assumes lower battery prices, higher fuel costs for ICEVs, and rapid technological development for BEVs. In contrast, the less optimistic scenario assumes higher battery prices, lower ICEV fuel costs, and slow technological development for BEVs.

Sensitivity analysis is frequently used to assess the impact of varying input parameters in the TCO calculation. In this analysis, a single input parameter is changed while the others are kept constant. A drawback of this approach is that it is a deterministic method that only explores one uncertainty parameter at a time. However, it is easy to implement and provides insight into the elements that have the most significant impact on the TCO. Gray et al. (2022), Hao et al. (2020), Mauler et al. (2022), Nykvist and Olsson (2021), Phadke et al. (2021) and Wu et al. (2015) all use sensitivity analysis to account for uncertainties in input parameters.

3.4 Uncertainty Elements

In addition to exploring how the literature handles uncertainty in TCO analyses, we study how to model the elements causing a large part of the uncertainty. This includes capital costs, infrastructure, and energy prices.

3.4.1 Capital Costs

Today, a higher upfront capital cost is associated with BETs than DTs. Since the market for BET is immature and the technology is new, significant cost changes are expected in a few years. According to Phadke et al. (2021), the cost differences between BETs and DTs are caused mainly by the battery and the drivetrain. Of these, they estimate the battery to cause the most significant cost difference.

The theory about learning curves can be useful in predicting future battery prices for BETs. One of the first known applications of applying a learning function to a task is Wright's learning curve from 1936 (Glock et al., 2019; Riahi et al., 2004). Wright (1936) showed that production time per airplane was reduced by a constant percentage when the production volume was doubled. The relation can be mathematically expressed as: $y = ax^{-b}$, where a is the time in hours to produce the first unit, x is the cumulative number of units produced, and $-b$ is a learning exponent that expresses improvements in time to produce the units as the cumulative production increases (Riahi et al., 2004; Wright, 1936). In this case, $b = -log(LR)/log(2)$, where LR is known as the learning rate. It is possible to apply Wright's theory about learning curves to technological learning in battery production. As the cumulative production of batteries increases, the unit cost of producing another battery is reduced. This is found in Mauler et al. (2021). They look into peer-reviewed studies on battery technology, present a review of 53 research articles on battery price predictions, and find that technological learning is a common approach to forecasting the prices of lithium-based batteries.

Another battery forecast approach mentioned in Mauler et al. (2021) is bottom-up cost estimations, where price forecasts are performed by estimating and adding together the individual components, resources, and processes needed to produce the battery. Other studies include expert interviews and projections based on the previously published literature to forecast battery prices. Based on the reviewed studies, Mauler et al. (2021) develop a combination model by fitting a function to the different predictions from the reviewed literature and predict battery prices to be as low as 71\$/kWh in 2050. However, a limited supply of raw materials might stop the prices from going as low as this prediction. This problem is addressed by Hsieh et al. (2019), who develop a technological learning model for battery pack prices in which they add a lower bound on the future price. They argue that raw material costs constrain how low the future battery pack price will be.

3.4.2 Infrastructure Costs

Heavy-duty transportation puts higher requirements on the charging infrastructure than battery electric passenger cars in terms of charging effect and space requirements. Upgrades to existing charging stations or the establishment of new facilities will therefore add to the cost of charging. Most of the existing literature, such as Figenbaum et al. (2019), Noll et al. (2022), Nykvist and Olsson (2021), Phadke et al. (2021), and Wu et al. (2015)

do not account for uncertain infrastructure build-out for trucks when calculating TCOs.

Lajevardi et al. (2022) include infrastructure uncertainty by looking at two different scenarios for the speed of infrastructure build-out. The slow development scenario includes development around major freight terminals from 2020 to 2040, whereas the rapid development scenario includes building out charging stations around major freight terminals from 2020 to 2030 and then development to remote areas in 2040. The scenarios are then included in an intangible cost for refueling inconvenience added to the TCO. Refueling inconvenience accounts for all expenses associated with refueling other than the fuel price itself. Based on Miller et al. (2017), it is a function of transport distance, trucker wage, refueling time, and station availability. Lin et al. (2018) also refer to refueling inconvenience and use it to calculate the additional cost associated with filling hydrogen. Furthermore, in the deployment planning for FCET filling stations, Greene et al. (2020) explain that the goal is often to maximize refueling convenience, meaning that stations should be placed so that the additional refueling inconvenience is minimized. For FCEVs and BEVs, Kang and Recker (2014) measure the individual level of inconvenience of operating an alternative fuel vehicle. By assuming a time value of 30$ per hour and calculating the refueling inconvenience in two different scenarios for charging speed, they find that the refueling inconvenience is significantly reduced by using high-speed charging.

If the infrastructure is built out, it is likely that a queue will occur. Time spent in a queue at charging stations increases the cost for trucking companies and is addressed in queuing theory. Harris et al. (2008, p. 2) define a queue as a system where customers arrive, possibly wait for service, and then leave the system after they have been served. Gnann et al. (2018) develop a queuing model for charging electric passenger cars in Norway and Sweden. They represent charging times with a normal distribution and arrival rates with an exponential distribution. Alp et al. (2022) include queuing costs and establishment costs for infrastructure as an integrated part of the investment strategy for a company transitioning to BETs. They emphasize the importance of a high density of charging infrastructure since this leads to less queuing time and fewer detours.

When new charging facilities with high-power chargers are built, the existing electricity grid might be unable to handle the associated load increase that the charging facility causes. Different options for handling heavy loads on the transmission grid are found in the literature. For example, vehicle-to-grid (V2G) technology can potentially deal with varying charging demand during the day (Al-Hanahi et al., 2022; Tarroja et al., 2016; Wang et al., 2022). Another alternative includes using battery energy storage systems (BESS) (Tarroja et al., 2016; Wang et al., 2022), which are stationary storage systems used to charge vehicles during demand peaks and recharge when the grid demand is lower. Tarroja et al. (2016) find that the flexibility with stationary storage systems is higher than for V2G systems since driving patterns and vehicle battery size affect the performance of the V2G systems. A third option is battery swapping, in which the entire battery is replaced by a fully charged one. Zhu et al. (2023) find that this is the most cost-effective energy supply mode for trucks doing medium-distance driving and argue that this method will be further expanded with battery technology improvement. The main advantage of battery swapping is that the time used for energy supply is reduced. However, Ahmad et al. (2020) highlight that there are several challenges, including lack of battery ownership, battery degradation, feasibility in terms of robustness of batteries, and interchangeability of batteries between different brands. Additionally, the cost of the battery-swapping activity might be too high for it to be feasible in practice (Xu et al., 2017).

3.4.3 Energy Costs

Phadke et al. (2021) argue that decreasing battery costs towards 2030 imply that the charging costs will make up a more significant part of BET costs in the future. In general, electricity is difficult to store, which makes it different from other commodities (Shahidehpour et al., 2003, p.163). The non-storability requires a balanced relationship between power production and power demand to get stability in the power system (Kaminski, 2013, p.767). Moreover, power demand and supply are weather dependent. These features lead to price dynamics not observed in other markets. For this reason, a lot of research is conducted on this market, and an extensive literature summary is provided by Weron (2014).

When forecasting electricity prices, the short-term time frame typically encompasses minutes to a few days ahead, medium-term forecasting is from a few days to months ahead, while long-term covers a few months and up to years ahead forecasting. Statistical models are often applied to short-term electricity price forecasting. These models use previous prices in combination with exogenous variables to predict prices (Weron, 2014). Computational intelligence techniques, such as artificial neural networks (ANNs) and support vector machines (SVMs), can also be used for electricity price forecasting. These models require a large amount of training data but have the advantage of handling complex patterns and non-linearity. However, a challenge for both of the mentioned models is their limited ability to forecast long-term.

Another electricity price forecasting technique is agent-based simulation models, in which the price is determined by supply and demand. Koritarov (2004) finds that these models are suitable for long-term price forecasting. A similar finding is done by Ziel and Steinert (2018). They point out that few studies on medium and long-term electricity price forecasting are conducted and find that supply and demand-based models perform well for these applications. Supply and demand models are provided in Vagner et al. (2022) and Gunnerød et al. (2023) on behalf of Statnett (Norwegian TSO) and Birkelund et al. (2021) on behalf of NVE (The Norwegian Water and Energy Directorate). Their analyses are based on estimates of future energy production and demand in Europe in the coming years. Both use simulations of 29-30 historic weather scenarios to predict future electricity prices. The average of the simulated prices is then calculated as the projected electricity price. This approach can capture the weather dependency seen in the Norwegian power market.

The future price of diesel determines the energy costs for DTs. According to EIA (2022), there is a strong correlation between the diesel price and the price of crude oil. We, therefore, look at crude oil predictions to get estimations for the future diesel price. Behmiri and Manzo (2013) review the existing literature on crude oil forecasting and divide them into qualitative and quantitative methods. Qualitative methods look at the effect qualitative factors, such as unforeseen political events or natural disasters, have on the crude oil price. They group quantitative methods into econometric- and computational methods. Econometric models include time series models, financial models, and structural models. Of the existing computational models, artificial neural networks (ANNs) and support vector machines (SVMs) are the most common. According to Behmiri and Manzo (2013), most quantitative methods focus on short and medium-term predictions. More recently, Funk (2018) explores the predictive performance of forecast combination models on the crude oil price. He finds that a model combining different forecasting techniques performs better than the best individual model for medium-term forecasting (3-12 months).

Every year EIA publishes projections of the crude oil price in Annual Energy Outlook

(EIA, 2023a). These projections are created using National Energy Modeling System (NEMS), which is a modular-based system. NEMS balances the energy supply and demand for every type of fuel and consumption sector, considering the economic competition among different energy sources and fuels (EIA, 2023b). The result is projections for the supply, demand, and price of various energy sources in different development scenarios. Annual Energy Outlook 2023 contains annual projections from 2021 to 2050, which can be used to calculate the future diesel price.

3.5 Stock-Flow Models

Stock-flow models are macroeconomic models that integrate the stocks and flows of all sectors of the economy based on distinctive accounting rules (Caverzasi & Godin, 2014). For transportation, stock-flow models can be used to simulate the development of the overall vehicle fleet by estimating the inflow and outflow of vehicles. BIG is the Norwegian stock-flow model, which can project the development of the vehicle fleet until 2075 (Fridstrøm & Østli, 2016). The model uses the Markov-chain principle, where the vehicle stock in a given year is determined by the stock from the previous year, adjusted for the flow of vehicles between the years. These flows can be either negative or positive, where negative flows represent vehicles that are deregistered or replaced, and positive flows indicate newly registered vehicles. By employing various assumptions for government support schemes, stock-flow models can be used to calculate how the timing of the optimal investment decision in BETs impacts the composition of the overall fleet.

3.6 Discounting

The discount rate is the rate of return that the suppliers of capital are compensated for the risk they bear in a project (Peterson & Fabozzi, 2002, p. 5). The discount rate affects the estimated total cost of owning and operating a truck. To compare investments in DTs and BETs, future costs for both options must be discounted back to the present value. From the perspective of a firm considering investing, the discount rate is the cost of capital (Peterson & Fabozzi, 2002, p. 5). Gollier (2013) refers to discounting rate as putting a *price on time* (p. 5) because there is a value related to delaying the investment. The weighted average cost of capital (WACC) is commonly used as a discount rate in the literature. A firm's WACC is its estimated cost of debt and equity, weighted by the proportion of each capital source (Peterson & Fabozzi, 2002, p. 159). The discount rate that firms use will therefore vary depending on the source of financing and the cost of each capital source for the specific company. Gray et al. (2022), Noll et al. (2022), and Phadke et al. (2021) use discount rates of 6.0%, 6.9% and 7.0%, respectively. Miljødirektoratet (2020) emphasizes that the discount rate also reflects investment risks and a liquidity price in cases where the firm's liquidity is poor. They use a discount rate of 9.5% for the road transport sector in their calculations. This could be because many trucking companies are small businesses with limited liquid assets and a lower risk tolerance, requiring a higher discount rate.

The public sector also needs tools to evaluate investment decisions but will usually consider other aspects beyond financial benefits when deciding if a project is worth investing in. Cost-Benefit Analysis (CBA) is a common method for evaluating public sector investments at a large scale, aiming to maximize the benefit to the society (Addae-Dapaah, 2012).

When evaluating the NPV of a project, the social discount rate is typically used to convert all future benefits to the present value. CBA aims to put a monetary value on all project factors, including externalities for which no price exists, which are then summarized to evaluate if the project is beneficial or not (Sirnes et al., 2021). This analysis deviates from a firm's investment decision because the aim is to include all benefits and inconveniences of the project as a whole. Usually, the discount rate is lower for public projects than for firms maximizing profits. For example, the Norwegian government recommends a discount rate of 4% (Finansdepartmentet, 2021).

3.7 Research Gap and Our Contributions

The current research on investments in BETs mainly focuses on how a limited number of uncertain elements influence investment decisions. Furthermore, studies usually assume that charging infrastructure is present, which is not the case. This results in cost estimations that are lower than the actual costs for a trucking company. Additionally, a lot of the research on uncertainty and electric vehicles is more focused on electric passenger cars. There is also a research gap relating to an investment model that companies can use directly and that emphasizes the differences among the companies. Trucking companies that rely on public infrastructure to operate BETs will especially benefit from research in this area. Our contribution is, therefore, a stochastic TCO model for the investment decision, which includes multiple elements of uncertainty and various scenarios for infrastructure development. This is further used to determine the most efficient governmental measures that can make BETs cost-competitive. We segment both on company size and transport distance, which gives a broader understanding of how cost uncertainty affects different types of companies.

3.8 Relevant Literature on TCO Modeling

A summary of the reviewed literature on TCO modeling is included in Table 3.1. The studies use either Monte Carlo simulations, scenario modeling, or case studies to model the TCO. The majority of the studies do not include infrastructure uncertainty when modeling the TCO. Segmentation based on transport distance is common, but we have found no other models that segment based on company size. Some studies use distributions for future electricity and diesel prices to deal with uncertainties, while others hold this constant during the investigated period. Most studies use declining cost functions, distributions, or scenarios to model future battery prices.

Table 3.1: Classification of related literature on TCO modeling. Technology: BE = Battery Electric, FCE = Fuel Cell Electric, D = Diesel, P = Petrol, PHE = Plug-in Hybrid Electric, NG = Natural Gas. Vehicle: T = Truck, PC = Passenger Car, B = Bus. Uncertainty handling: CS = Case Study, MC = Monte Carlo, Sce = Scenarios, Sen = Sensitivities. Infrastructure uncertainty handling: Sce = Scenarios, RI = Refueling Inconvenience. Other abbreviations: Sce = Scenarioes, Dist. = Distribution, Const. = Constant

Paper	**Technology**	**Vehicle**	**Area**	**Uncertainty handling**	**Electricity prices**	**Diesel prices**	**Battery prices**	**Infrastructure uncertainty handling**	**RI cost estimation**	**Segmentation**
Mauler et al. [2022]	BE, D, FCE	T	U.S.	Sce, Sen	Sce	Const.	Sce	-	-	Transport distance (Long-haul)
Nykvist and Olsson [2021]	BET, DT	T	Generalized study	Sce, Sen	Const.	Const.	Sce	-	-	Not specified
Gray et al. [2022]	BE, D, FCE, NG	T	Generalized study	MC, Sen	Sce	Const.	Triangular dist., input for 2025, 2030 and 2040.	Sce	-	Transport distance (Short-haul, Long-haul)
Phadke et al. [2021]	BE, D	T	US	CS, Sen	Const.	Const.	Const., values for 2020 and 2030.	-	-	Transport distance (Short-haul, Long-haul)
Noll et al. [2022]	BE, D, FCE, PHE, NG	T	Europe (10 countries)	MC	Normal dist., const. input	Normal dist., const. input	PERT dist, const. input	-	-	Transport distance (Urban, Regional, Long-haul)
Lajevardi et al. [2022]	BE, NG, PHE, FCE	T	Canada	MC, Sce	Uniform dist., time-varying input	Uniform dist., time-varying input	Declining cost function	Sce & RI	Wage	Transport distance (Short-haul & long-haul)
Figenbaum et al. [2019]	BE, D, FCE	PC, T, B	Norway	CS	Const.	Const.	Declining cost function	-	-	Transport distance (Short-haul & long-haul)
Hao et al. [2020]	BE, D, PHE	PC	China	MC, Sce, Sen	Const.	Gamma dist., time-varying input	Declining cost projections	-	-	-
Wu et al. [2015]	BE, D	PC	Germany	MC, Sen	PERT-dist., const. yearly increase	PERT-dist., constant yearly increase	PERT dist, declining input	-	-	-
Vanhaverbeke et al. [2017]	BE, D, P, NG, PHE	PC	Belgium	MC	Triangular dist., const. input	Normal dist., const. input	-	-	-	-
Our model	BE, D	T	Norway	MC, Sce, Sen	PERT-dist., time-varying input	PERT-dist., time-varying input	Declining cost function	Sce & RI	Trucking company estimations	Transport distance (Short-haul, Mixed, Long-haul) Truck fleet size

Chapter 4

Methodology

This chapter presents the methodology for calculating the TCO for BETs and DTs with multiple elements of uncertainty. First, in Section 4.1, we provide the general formula for the TCO. Then, in Section 4.2, we describe how capital costs are calculated, focusing on the future price of batteries and the chassis. Section 4.3 describes how operational costs are calculated. This includes electricity- and diesel price forecasting and infrastructure uncertainty. Lastly, Section 4.4 describes how we develop a stock-flow model to determine the effect different government support schemes have on the national truck fleet. The nomenclature used in this chapter is shown in Table 4.1.

4.1 TCO Calculation

To compare DTs and BETs, we calculate the TCO using Monte Carlo simulations. We extend the methodology used in our project thesis (Krüger & Thiis, 2022) by including declining capital costs and scenarios for infrastructure development. We also consider a sequential investment decision and segment based on trucking company sizes and transport distance.

We split the TCO into capital costs (CAPEX) and operating costs (OPEX) and calculate the TCO for each year t. Operational costs are calculated each year the truck is used and then discounted to present value. This is shown in (4.1):

$$TCO_t = CAPEX_t + \sum_{n=1}^{N} \frac{OPEX_{t+n}^{s,r}}{(1+\rho)^n}, \tag{4.1}$$

where $CAPEX_t$ is the capital expenditures in year t, $OPEX_{t+n}^{s,r}$ is the operational expenditures in year $t+n$ for a company with size s and transport distance r, N is the lifetime of the truck, and ρ is the discount rate.

Table 4.1: Nomenclature used in TCO calculation.

	Description
$A_t^{j,r}$	Total truck fleet in year t
C_t^k	Cost of component k in year t (NOK)
Cap_t^{BET}	Battery capacity for BET in year t (kWh)
D	Annual driving distance (km)
E	Energy consumption (kWh/km or l/km)
$G_t^{j,r}$	New trucks in year t
$H_t^{j,r}$	Trucks leaving the fleet in year t
I_t^{BET}	Investment cost for a BET in year t (NOK)
I_t^{DT}	Investment cost for a DT in year t (NOK)
M	Mandatory break time (hours)
N	Lifetime of truck (years)
O	Operational days per year (days)
P_t^{k}	Price of component k in year t (NOK)
$RI_t^{s,r}$	Refueling inconvenience in year t (NOK/year)
$StA_t^{s,r}$	Station availability in year t
j	Truck technology (BET or DT)
k	Cost component
n	Number of years since investment
r	Transport distance
s	Company size
t	Year
α	Residual value rate
β	Investment support rate
γ	Gross profit
ρ	Discount rate

4.2 Capital Costs

CAPEX for BETs is calculated by deducting the residual value, discounted back to present value, and the government investment support from the investment cost. DTs have no investment support, so CAPEX is the investment costs minus the residual value. Equations (4.2) and (4.3) show CAPEX for BETs and DTs, respectively:

$$CAPEX_t^{\mathrm{BET}} = I_t^{\mathrm{BET}} - \alpha \frac{I_t^{\mathrm{BET}}}{(1+\rho)^N} - \beta(I_t^{\mathrm{BET}} - I_t^{\mathrm{DT}}), \tag{4.2}$$

$$CAPEX_t^{\mathrm{DT}} = I_t^{\mathrm{DT}} - \alpha \frac{I_t^{\mathrm{DT}}}{(1+\rho)^N}, \tag{4.3}$$

where I_t^{BET} (I_t^{DT}) is the initial investment cost for BETs (DTs), N is the lifetime of the truck, ρ is the discount rate, α is the residual value rate, and β is the government support rate.

The BET investment cost is split into three components; battery, body, and chassis. The powertrain and cab are considered parts of the chassis. For DTs, the cost components are the body and chassis. Equation (4.4) denotes investment costs for BET, while (4.5) represents investment cost for DTs:

$$I_t^{\mathrm{BET}} = C_t^{\mathrm{Bat}} + C_t^{\mathrm{Body}} + C_t^{\mathrm{Chas}}, \tag{4.4}$$

$$I_t^{\mathrm{DT}} = C_t^{\mathrm{Body}} + C_t^{\mathrm{Chas}}. \tag{4.5}$$

The following subsections explain how we model the future values of these components.

4.2.1 Battery

Battery prices are expected to decline due to technological development and increased production volumes. We assume that this will lead to a rapid reduction in battery prices in the beginning, but after some time, improvements in technology will be more subtle. This will lead to smaller price reductions. Later, prices will level off since a limited supply of necessary raw materials will be a constraint. We, therefore, fit an exponential decay function to historic battery prices and future battery price predictions. This is shown in (4.6):

$$P^{\mathrm{Bat}}(t) = a \cdot e^{-b(t-x+1)} + c,\ t \geq x \tag{4.6}$$

where a, b and c are the fitted parameters, t is the prediction year, and x is the initial year with battery price data used to fit the function. The output of this function is the predicted price in NOK/kWh for the battery in year t. The battery cost in year t is given by the battery price multiplied by the battery capacity (in kWh) and is shown in (4.7):

$$C_t^{\mathrm{Bat}} = P_t^{\mathrm{Bat}} \cdot Cap_t^{\mathrm{BET}}. \tag{4.7}$$

4.2.2 Body and Chassis

The truck body is designed based on the type of goods transported, and price variations are expected. However, since the body is the same independent of drivetrain technology, the body cost is assumed fixed.

The chassis cost includes the powertrain, the cab, and the chassis structure. We assume that chassis costs are the same independent of goods transported. With the increased adoption of BETs, we expect the costs of BET chassis to decline and fit an exponentially decaying cost function to price predictions. This has the same functional form as Equation 4.6, with different values for the fitted parameters, and is chosen because more learning is expected initially. We further assume that the DT chassis cost stays constant.

4.3 Operational Costs

OPEX consists of all costs occurring when operating the vehicle throughout its lifetime. We exclude labor costs from the calculation since it is assumed to be independent of the trucking technology. The annual operational cost is the sum of maintenance costs, toll costs, other operating costs, energy costs, and refueling inconvenience, as given by (4.8):

$$OPEX_t^{s,r} = C_t^{\text{Maintenance}} + C_t^{\text{Toll}} + C_t^{\text{Other var. cost}} + C_t^{\text{Energy},r} + RI_t^{s,r} \tag{4.8}$$

for $s \in$ {small, medium, large company} and $r \in$ {short-haul, long-haul, mixed}.

All parameters will have different values for BETs and DTs. Maintenance, toll, and other variable costs are deterministic and assumed constant. The energy cost is the charging cost per kWh (for BETs) or diesel cost per liter (for DTs), multiplied by the consumption per km and yearly driving distance. This is given by (4.9):

$$C_t^{\text{Energy},r} = P_t^{\text{Energy}} D^r E \tag{4.9}$$

for $r \in$ {short-haul, long-haul, mixed},

where P_t^{Energy} is the energy price in year t, D^r is the annual driving distance for transport distance r, and E is energy consumption per km.

Section 4.3.1 and Section 4.3.2 describe how the charging cost and diesel cost are calculated. Refueling inconvenience is the additional intangible cost associated with refueling energy that is not related to energy costs. This is further elaborated on in Section 4.3.3.

4.3.1 Charging

For BETs, the energy price is the charging price, which is the amount trucking companies pay per kWh for electricity. The charging price consists of the electricity price, charging station surcharge, and other electricity costs. We do not include possible governmental electricity support. The energy price for BETs is thus given by (4.10):

$$P_t^{\text{Energy}} = P_t^{\text{Charging}}(\text{NOK/kWh}) = P_t^{\text{Electricity}} + P_t^{\text{Surcharge}} + P_t^{\text{Other el. costs}}. \tag{4.10}$$

We consider the charging station surcharge and other electricity costs as deterministic parameters. The charging station surcharge is the amount paid to the charging station operator. Without governmental support, this will most likely represent the most significant part of the future charging cost (F. Rømo, personal communication, 01.11.22). Private charging, either done at home with the driver or at the company property, does not have any surcharge. The electricity costs include the transmission charge, the electricity supplier surcharge, and government fees and taxes. These are a small part of the final charging costs. Based on historical data from SSB (2022d), we assume these to be fixed. We consider the annual electricity price a stochastic process and use long-term annual electricity forecasts to model its behavior. Since we do not know the probability distribution of future electricity prices, we use the PERT distribution. This takes in the minimum, most likely, and maximum values as input parameters and is a common way to model expert estimates (Vose, 2008). The annual electricity price in year t is given by (4.11):

$$P_t^{\text{Electricity}} = PERT(P_t^{\text{Min}}, P_t^{\text{Base}}, P_t^{\text{Max}}), \tag{4.11}$$

where

P_t^{Min} = Minimum predicted electricity price in year t,
P_t^{Base} = Base case electricity price prediction in year t,
P_t^{Max} = Maximum predicted electricity price in year t.

The PERT distribution is given by (4.12) (Vose, 2008) :

$$PERT(a, b, c) = Beta(\alpha_1, \alpha_2)(c - a) + a, \tag{4.12}$$

where

$$\alpha_1 = \frac{(\mu - a)(2b - a - c)}{(b - \mu)(c - a)},$$

$$\alpha_2 = \frac{\alpha_1(c - \mu)}{(\mu - a)},$$

$$\mu = \frac{a + 4b + c}{6}.$$

Figure 4.1 shows the PERT distribution, where a, b, and c are values for minimum, most likely, and maximum, respectively. The PERT distribution weights the most likely value four times higher than the minimum and maximum. This makes it less sensitive to extreme values than, for example, the uniform distribution. Furthermore, the PERT distribution can never go beyond the stated minimum and maximum values, which makes it important to use input parameters of high quality. With this way of modeling, the price can jump from the minimum price one year to the maximum price the next. However, this is not a significant issue since the electricity price is largely weather dependent, and the weather is independent of the previous year.

4.3.2 Diesel

The energy price for DTs is the diesel price per liter. EIA (2023c) explains that the US diesel price comprises the crude oil price, refinery costs, distribution & marketing costs, and taxes. Transferring this to the Norwegian market specifications, which are explained in Section 2.4.2, the diesel price per liter is the sum of the crude oil price, refinery costs, CO_2 tax, and road use tax. Additionally, the price is divided by $1 - \gamma$, where γ is the gross profit for the gas stations. We assume a constant USD to NOK exchange rate and disregard currency fluctuations that could affect the international diesel price. Thus, the energy price for DTs is given by (4.13):

$$P_t^{\text{Energy}} = P_t^{\text{Diesel}}(NOK/l) = \frac{P_t^{\text{Crude oil}} + P_t^{\text{Refining}} + P_t^{CO_2 \text{ tax}} + P_t^{\text{Road tax}}}{1 - \gamma}. \tag{4.13}$$

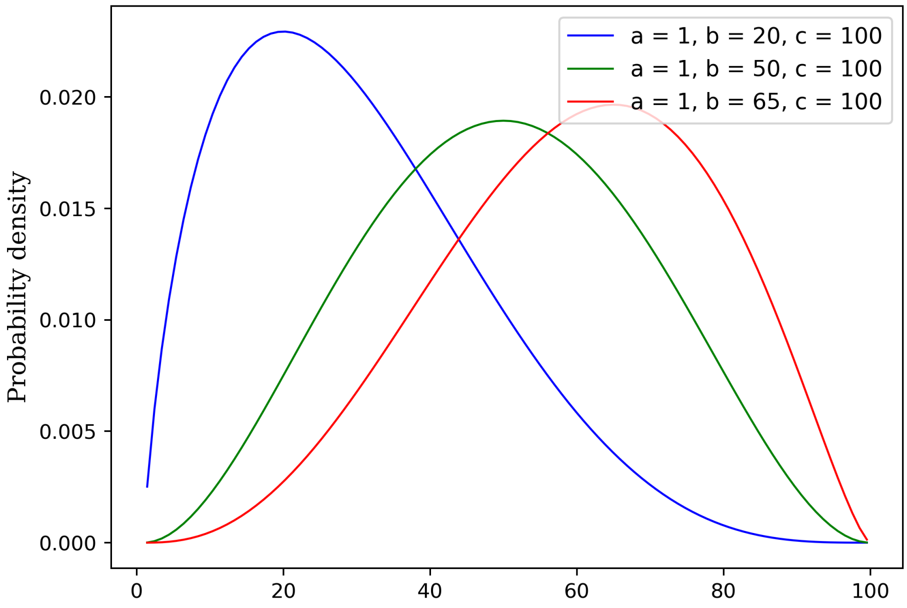


Figure 4.1: Examples of PERT(a,b,c) distributions, where a = minimum, b = most likely, and c = maximum.

We consider refinery costs and taxes as deterministic parameters and the crude oil price a stochastic process. Even though refinery costs vary, the variations are smaller, and the cost constitutes a smaller part of the final price. This is therefore kept constant. For the CO_2 tax, we assume an annual increase from 2023 to 2030 due to the proposed increase by the government (Rustad, 2021). The road use tax is assumed constant based on historical data from SSB (2022c), which shows a marginal increase since 2012.

We use the PERT distribution to model the future price of crude oil for the same reasons as explained for the electricity price in Section 4.3.1. However, in this case, we use returns to model the price movements from one year to the next. This way, the price will not move from the lowest possible in one period to the highest possible in the next. This is to better represent the price movements since global events, such as war, tend to affect the crude oil price for more than one period. When using returns in the PERT distribution, more of this effect is captured. The returns are obtained by dividing the minimum and maximum values by the base projection of the previous year. Figure 4.2 shows an example of 20 simulations of the crude oil price movements using returns when the investment year is 2024. To avoid the simulated values being below or above EIA's minimum and maximum values, we restrict the price from going beyond these. Thus, the annual crude oil price in year t is given by (4.14):

$$P_t^{\text{Crude oil}} = P_{t-1}^{\text{Crude oil}} \cdot PERT(\frac{P_t^{\text{Min}}}{P_{t-1}^{\text{Base}}}, \frac{P_t^{\text{Base}}}{P_{t-1}^{\text{Base}}}, \frac{P_t^{\text{Max}}}{P_{t-1}^{\text{Base}}}), \tag{4.14}$$

$$P_t^{\text{Min}} < P_t^{\text{Crude oil}} < P_t^{\text{Max}},$$

where

P_t^{Min} = Crude oil projection in low oil price scenario in year t,
P_t^{Base} = Crude oil projection in base case scenario in year t,
P_t^{Max} = Crude oil projection in high oil price scenario in year t.

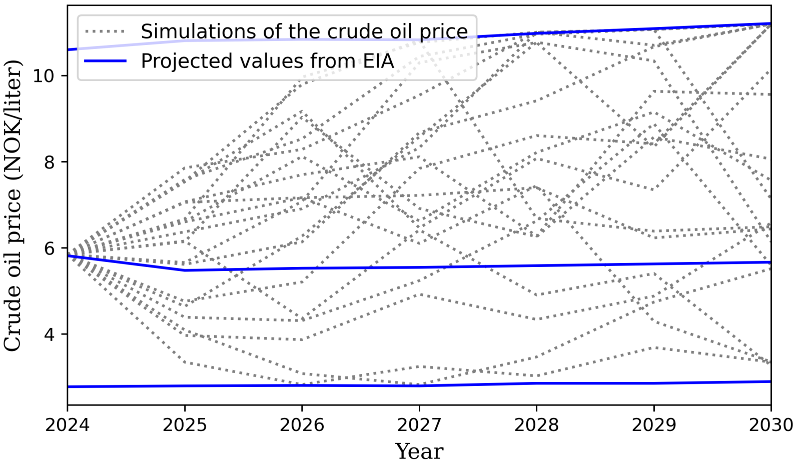


Figure 4.2: Example of crude oil price movements using returns. The investment year is 2024.

4.3.3 Refueling Inconvenience

We define refueling inconvenience as the cost of refueling that is not related to the fuel price itself, in line with Miller et al. (2017). This is an intangible cost that includes refueling time and the availability of sufficient infrastructure. The refueling inconvenience is zero for DTs, whereas, for BETs, it represents an operational cost. We base the formula for refueling inconvenience on the formulas used in Lajevardi et al. (2022) and Miller et al. (2017), with some modifications and specifications. The annual refueling inconvenience is given by (4.15):

$$RI_t^{s,r} = C_t^{\text{Wait}} \cdot (RT^r \cdot StA_t^{s,r} - B) \cdot O, \qquad RI_t^{s,r} > 0, \tag{4.15}$$

for $s \in$ {small, medium, large} and $r \in$ {short-haul, long-haul, mixed},

where C_t^{wait} is the hourly waiting cost, RT^r is the refueling time, $StA_t^{r,s}$ is the station availability parameter, B is the mandatory break time, and O is operational days per year.

The waiting cost is the hourly cost for the trucking company if the transport is delayed, and the refueling time is the time spent charging. The station availability parameter is a constant that determines the availability of public charging stations in the given year and scenario. The parameter varies depending on company size and transport distance because the availability affects them differently. The mandatory break time for truck drivers is subtracted from the expression because we assume that they can use this break to recharge. Lastly, the entire expression is multiplied by the number of working days per year to get the annual refueling inconvenience cost.

We calculate the refueling inconvenience based on the company size (s) and transport distance (r). This segmentation is chosen because responses from our survey to NLF members indicate that smaller companies drive more varied routes and value the flexibility in usage higher. Larger companies also have the possibility to have a mixed fleet, which makes them able to switch between vehicles depending on suitability for the assignment. This could, for example, mean that they could own some BETs to use for distances that have charging facilities and some DTs to use for other assignments. The consequences of insufficient infrastructure are, therefore, more significant for small companies. Additionally, we separate between short-haul, long-haul, and mixed transportation. The latter includes companies that do a combination of short- and long-haul transport. This is because charging stations will likely be built around major terminals and cities first, making the infrastructure more available to certain segments.

We define the scenarios *slow build-out*, *base*, and *rapid build-out* of charging infrastructure, where each scenario corresponds to a government support rate for infrastructure development. Political decisions to invest in public infrastructure for charging can enable a transition between scenarios. Each scenario consists of three stages of development, with various lengths of each stage. The stage of development, in addition to the company size (s) and transport distance (r) specification, determines the weight of the station availability parameter. The station availability parameter takes discrete values from 1 to 5. Based on the methodology in Lajevardi et al. (2022), we assume the following stages of development:

- Stage 1 includes development around major freight terminals. This could be suitable for short-haul transportation where vehicles return to their base after each assignment. Additionally, it could be suitable for large companies doing mixed transportation to replace part of their fleet with BETs.
- Stage 2 includes the development of public charging infrastructure around large cities and major destinations. For short-haul transportation, charging infrastructure is more available in cities. For long-haul transportation, infrastructure is available for those driving fixed routes between major destinations.
- Stage 3 includes the development of charging stations in remote areas. In this stage, infrastructure is assumed to be built out at a sufficient level so that the station availability parameter is set to 1 for all company segments.

4.4 Stock-Flow Modeling

We use stock-flow modeling to simulate the composition of the national truck fleet in different scenarios. Our approach is a special case of the BIG model used by TØI (Fridstrøm & Østli, 2016). The BIG model uses long-term scenario projections to model the composition of multiple energy technologies in the fleet. On the other hand, our model uses TCO analysis to estimate when truck owners invest in BETs instead of DTs and is limited to these technologies. The total stock of BETs and DTs in year t for transport distance r, is denoted by $A_t^{j,r}$ and given by (4.16):

$$A_t^{j,r} = A_{t-1}^{j,r} + G_t^{j,r} - H_t^{j,r} = A_{t-1}^{j,r} \cdot \left[1 + \frac{G_t^{j,r} - H_t^{j,r}}{A_{t-1}^{j,r}} \right] \tag{4.16}$$

$$\text{for } \; j \; \in \; \{\text{BET, DT}\} \text{ and } \; r \; \in \; \{\text{short-haul, long-haul, mixed}\},$$

where $G_t^{j,r}$ denotes investments in new trucks, $H_t^{j,r}$ is outgoing trucks, $A_{t-1}^{j,r}$ is the fleet size in the preceding year, and $\left[1 + \frac{G_t^{j,r} - H_t^{j,r}}{A_{t-1}^{j,r}}\right]$ is similar to the transition rate in the BIG model.

New investments are either BETs or DTs, depending on the optimal investment decision derived from TCO analysis. The demand for new trucks in year t is the amount of the fleet that is replaced, adjusted for expectations of future increase or decrease in road transportation demand. Each transport distance r has a share of the total fleet, which is constant throughout the period of interest.

The total fleet in year t is the sum of the number of trucks doing short-haul, long-haul and mixed transportation:

$$A_t = A_t^{short-haul} + A_t^{long-haul} + A_t^{mixed}, \tag{4.17}$$

where the fleet composition in each transport distance is given by:

$$A_t^r = A_t^{BET,r} + A_t^{DT,r} \text{ for } r \; \in \; \{\text{short-haul, long-haul, mixed}\}. \tag{4.18}$$

Chapter 5

Case Study

In this chapter, we present the data used in our methodology to give a detailed case study for Norway. In Section 5.1, we present the input parameters used for estimating capital costs. The main focus is on battery and chassis cost predictions. In Section 5.2, we present the data used for operational costs. This includes charging costs, diesel costs, refueling inconvenience, toll and ferry, maintenance, and other variable costs. We then present the discount rate in Section 5.3. In Section 5.4, we explain the assumptions used in the stock flow modeling of the truck fleet. Lastly, Section 5.5 summarizes the deterministic parameters in a table. The implementation of this case in Python can be found in Krüger and Thiis (2023).

5.1 Capital Costs

We consider a government support rate of 40% and a residual value rate of 20%. We use a three-axled heavy-duty truck with a 6x2 axle configuration and a battery size of 540 kWh. This is a typical truck for the Norwegian market, according to communication with a manufacturer of trucks. The mentioned manufacturer estimates that the chassis cost including the battery for this truck type is around 3.50 - 3.65 MNOK for a BET and 1.35 - 1.45 MNOK for a DT in 2023. The body cost depends on the type of goods being transported. Since body cost is the same independent of technology, we use a fixed cost of 1 MNOK in our analysis.

We use predictions from Mauler et al. (2021) to estimate battery prices and fit an exponentially decaying function. Since these predictions represent an optimistic case for battery prices, we fit a curve using future prices that are 20% higher. Battery price curves and predictions are shown in Figure 5.1. A constant exchange rate of 10 USD to NOK is used, and the battery price is multiplied by the battery size to get the truck battery price estimation in the given year. According to the battery price prediction curve in Figure 5.1, battery prices are around 1 700 NOK/kWh in 2023. For a 540 kWh battery, the cost will be around 918 KNOK. When subtracting the cost of the battery from the estimated price range of 3.55 - 3.65 MNOK for a chassis that includes the battery, the cost of the chassis alone is approximately 2.7 MNOK in 2023.

We rely on estimations from Figenbaum et al. (2019) to estimate future chassis costs. They predict that small-scale serial production of BETs will occur in 2025, and mass production will be achieved in 2030. Based on these assumptions, they estimate total BET costs to

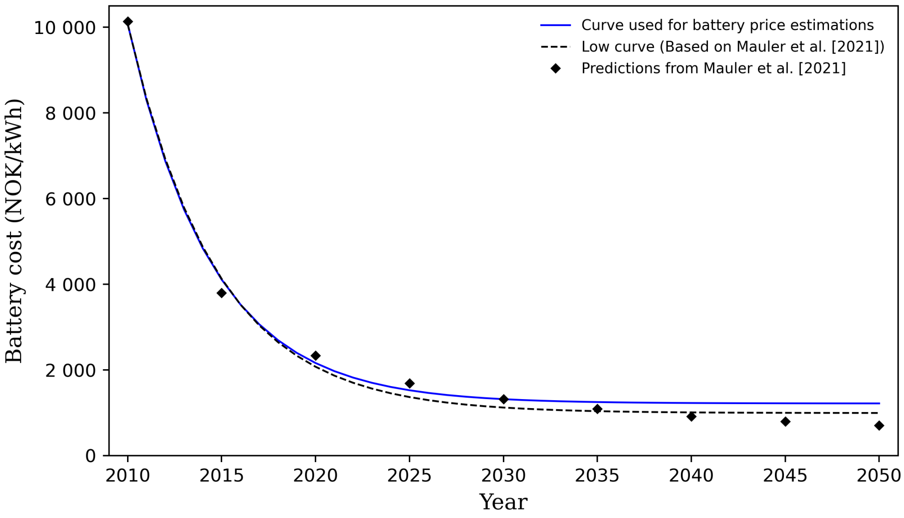


Figure 5.1: Estimations of future battery prices in NOK/kWh.

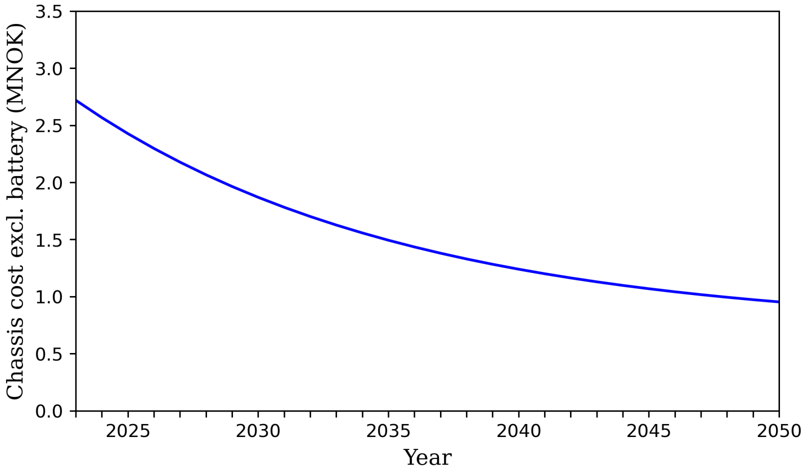


Figure 5.2: Estimations of future BET chassis costs (excl. battery) in MNOK.

be 50% higher than DTs in 2030. In accordance with these findings, a BET is around 3.5 - 3.7 MNOK in 2030 if DT costs are constant at 2.45 MNOK. We further estimate that a BET chassis will reach the same cost level as a DT chassis in 2035, and by 2040, we anticipate that the BET chassis will be cheaper. In 2050, our estimate for BET chassis cost is 1 MNOK. We fit an exponentially decaying function to the estimated chassis costs, shown in Figure 5.2. The estimated BET chassis cost in a given year is calculated using this function.

We include an additional investment cost for BETs related to purchasing and installing charging equipment. The cost is estimated to be 40 KNOK. This is based on the upper bound for charging equipment for electric cars, which is 15 KNOK (Prisguiden, 2023). Installation depends on the charging power and the condition of the electrical installation. This typically costs between 15 - 25 KNOK (Viter, 2022). Since more power is needed for BETs than passenger cars, the upper bound is chosen. The cost estimations for BETs and DTs are summarized in Table 5.1.

Table 5.1: Capital cost components for BETs and DTs. Numbers are in KNOK. The battery costs and BET chassis costs are estimated using the price curves in Figure 5.1 and Figure 5.2.

	2023	***2030***	***2035***	***2040***	**Cost development**
		BET			
Chassis (excl. battery)	2 720	*1 870*	*1 495*	*1 241*	Exponential decay
Battery	918	*712*	*675*	*664*	Exponential decay
Body	1 000	*1 000*	*1 000*	*1 000*	Fixed
BET costs (excl. charger)	**4 638**	***3 582***	***3 170***	***2 905***	
Charging equipment	40	*40*	*40*	*40*	Fixed
BET costs (incl. charger)	**4 678**	***3 622***	***3 210***	***2 945***	
		DT			
Chassis	1 450	*1 450*	*1 450*	*1 450*	Fixed
Body	1 000	*1 000*	*1 000*	*1 000*	Fixed
DT costs	**2 450**	***2 450***	***2 450***	***2 450***	

5.2 Operational Costs

Operational costs include charging costs, diesel costs, refueling inconvenience, toll and ferry, maintenance, and other variable costs. The following subsections elaborate on how these components are found.

5.2.1 Charging

The charging cost is a function of the charging price, the distance traveled, and the energy consumption. The charging price is further split into the annual price of electricity, other electricity costs, and an additional surcharge for charging at the charging stations. The distance traveled varies depending on whether the company does short-haul, long-haul, or mixed transportation. We assume an annual distance of 60 000 km for short-haul, 100 000 km for long-haul, and 80 000 km for mixed transportation. The energy consumption is set to 1.7 kWh/km, based on personal communication with Frode Rømo in Sintef Industry (16.05.23). We further base the charging requirements on a truck with a battery size of 540 kWh but assume that only around 380 kWh of the battery is available for driving. This is based on the reported driving range and consumption from Volvo (2022) and Klingenberg (2022).

We separate between public high-speed charging, public slow charging, and at-home slow charging. At-home charging is defined as private charging, either done at the company property or at home with the driver. The energy usage per day is estimated using the yearly driving lengths, 230 operation days per year, and the consumption rate for BETs. Assuming that the truck is fully charged at the beginning of each day, we calculate how much public high-speed charging is required during the day to avoid a depleted battery. We then calculate the time this takes with a high-speed charger of 250 kW. Since public high-speed charging is the most expensive option, this is kept at a minimum. The amount of high-speed and slow charging is used together with the annual driving distance to estimate charging costs. The parameters are shown in Table 5.2.

Table 5.2: Driving distances and charging specifications for different transport distances. Assumes an available battery capacity of 380 kWh, a 250 kW fast charger, and 230 operation days in one year.

Transport type	**Annual driving distance (km)**	**% high-speed charging (public)**	**% slow charging (at-home or public)**
Short-haul	60 000	14%	86%
Mixed	80 000	36%	64%
Long-haul	100 000	49%	51%

Annual Electricity Price

We use annual electricity price predictions from Statnett, which are presented in Vagner et al. (2022) and Gunnerød et al. (2023). Vagner et al. (2022) predict prices short-term (2023 - 2027) and Gunnerød et al. (2023) predict long-term (2030, 2035, 2040 and 2050). These can be found in Appendix B. Both studies use demand-supply modeling and simulations over multiple weather scenarios to calculate the lowest, highest, and base values for the annual average electricity price. We use Vagner et al. (2022) between 2023 and 2027, and Gunnerød et al. (2023) from 2027 and onwards. The base prediction is used as the most likely value, and the lowest and highest simulation values are used as minimum and maximum values.

We have made some additional adjustments to the data. Vagner et al. (2022) and Gunnerød et al. (2023) do not contain the highest and lowest weather simulations for NO1 and NO5. Since price predictions for these zones are similar to NO2, we use these instead. Gunnerød et al. (2023) report prices for 2030, 2035, 2040, and 2050. We, therefore, use 2030 predictions between 2028 and 2032, 2035 predictions between 2033 and 2037, 2040 predictions between 2038 and 2045, and 2050 predictions between 2045 and 2050. Due to the frequent movement of trucks across electricity price zones and transport companies often being stationed in multiple areas, we use the same electricity price for all of Norway. Since we do not have data on how much transportation is happening in each region, we calculate a weighted average by giving each prize zone equal weight. The data used in the PERT distribution is presented in Table 5.3. We point out that much uncertainty is tied to electricity prices so far off in the future.

Table 5.3: Electricity prices in øre/kWh used as input in PERT distribution. Numbers are based on data from Vagner et al. (2022) and Gunnerød et al. (2023). The base case for CO_2 prices and fuel prices is used.

	Year								
Parameter	2023	2024	2025	2026	2027	2028 - 2032	2033 - 2037	2038 - 2045	2045-2050
Maximum	255	205	164	130	149	118	95	79	75
Most likely	95	67	52	41	50	44	52	41	39
Minimum	31	20	14	11	14	14	25	19	18

Other Electricity Costs and Surcharge

Other electricity costs include surcharge to the electricity provider, transmission charge, governmental fees, and taxes. These show some seasonal variations, but we consider a fixed yearly price as these variations can be neglected when calculating the annual charging price. The electricity supplier surcharge is set to 0.05 NOK/kWh, based on NorgesEnergi (2023). Transmission charge and governmental fees- and taxes are set to 0.14 NOK/kWh and 0.16 NOK/kWh, respectively, based on Tensio (2023). When adding these components, other electricity costs are set to 0.35 øre/kWh.

The surcharge for charging differs depending on the charging type. We look at three options: public high-speed charging, public slow charging, and at-home slow charging. We assume that charging during the day is public high-speed charging. Overnight charging is either at-home or public slow charging. As of March 16th, 2023, Kople takes approximately 6.49 NOK/kWh and 4.65 NOK/kWh in surplus for high-speed charging and slow charging, respectively (Kople, 2023). This is calculated by deducting the electricity price in NO1, which we assume is 2 NOK/kWh, from the stated charging prices. Table 5.4 summarizes the values used for the different charging options.

Table 5.4: Summary of charging price parameters for the different charging methods in NOK/kWh.

	Other electricity costs	**Surcharge**
Public high-speed charging	0.35	6.49
Public slow charging	0.35	4.65
At-home	0.35	0.00

5.2.2 Diesel

The diesel price consists of the crude oil price, refinery costs, CO_2 tax, the road use tax, and gross profit for the petrol station. The gross profit for the petrol stations (γ) is set to 10%. Based on personal communication with Frode Rømo in Sintef Industry (16.05.2023), we set the consumption rate to be 0.4 liter per km. The yearly driving distances used are the same as for BETs.

We use Brent spot price projections from the Annual Energy Outlook (AEO) 2023 by EIA (2023a) to model the possible movements of the crude oil price. AEO provides future energy market projections with different scenarios and assumptions about oil prices, technological development, and macroeconomic growth. We use the values from the scenarios *low oil price*, *reference case*, and *high oil price* as the minimum, most likely, and maximum values in the PERT distribution. Table 5.5 shows the values used in USD/barrel. These are further converted to NOK/liter by using an exchange rate of 10 USD to NOK and the fact that 1 barrel = 158.987295 liters.

The refinery costs are calculated using information from EIA (2023c) about the cost components of the US diesel price and their historical values. As of January 2023, refinery costs were 28%, and crude oil costs were 40% of the diesel costs. In January 2023, the average Brent spot price was 82.50$ per barrel. By dividing this by 0.4 and multiplying by 0.28, we obtain the refinery costs for this month. Converting this to NOK/liter, we get refinery costs equal to 3.63 NOK/liter. We assume this cost to be fixed.

Table 5.5: Crude oil price projections from Annual Energy Outlook 2023, converted to NOK/liter.

Year	**Low oil price**	**Reference case**	**High oil price**
2023	2.72	5.76	10.63
2024	2.78	5.82	10.60
2025	2.80	5.48	10.81
2026	2.81	5.53	10.84
2027	2.80	5.55	10.83
2028	2.86	5.59	10.98
2029	2.86	5.63	11.09
2030	2.90	5.67	11.21
2031	2.93	5.71	11.34
2032	2.97	5.76	11.28
2033	3.01	5.79	11.38
2034	3.01	5.83	11.58
2035	3.04	5.88	11.59
2036	3.09	5.92	11.56
2037	3.11	5.96	11.73
2038	3.12	6.00	11.50
2039	3.14	6.03	11.51
2040	3.09	6.06	11.52
2041	3.10	6.10	11.64
2042	3.10	6.13	11.72
2043	3.10	6.15	11.72
2044	3.13	6.18	11.79
2045	3.13	6.20	11.73
2046	3.18	6.25	11.72
2047	3.15	6.28	11.79
2048	3.19	6.31	11.93
2049	3.17	6.36	11.92
2050	3.23	6.37	11.95

Table 5.6 shows the values used for taxes. We assume the road use tax to be constant at the 2023 level, and the CO_2 tax to be increasing by 15% each year from 2021 when it was 1.58 NOK/liter. This yearly increase aligns with the government's proposed plan mentioned in Section 2.4.2. Since the actual increase from 2021 to 2023 has been more than an annual 15%, the tax is slightly lower in 2024 than in 2023. Nevertheless, we continue to base the tax level on the government's climate plan from 2021 to 2030 for the remaining years. After 2030, it is assumed that the tax will remain unchanged.

Table 5.6: Taxes incorporated into the diesel price (NOK/liter).

	Year									
Tax	2023	2024	2025	2026	2027	2028	2029	2030	...	2050
CO_2 tax	2.53	2.40	2.76	3.18	3.65	4.20	4.83	5.56		5.56
Road use tax	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92		2.92

5.2.3 Refueling Inconvenience

We define small companies as companies with 0 - 2 trucks, medium companies with 3 - 10 trucks, and large companies with ten or more trucks. We define short-haul transportation as local and regional transportation within a 100 km range from the truck base. Long-haul transportation is defined as transportation in which an overnight layover is required for the driver. This is usually within a 500 km range. Mixed-haul transportation is companies that do a combination of these two.

We consider 750 NOK/hour as the waiting cost. This is based on the responses from our survey to NLF members in which 25% selected 501 - 750 NOK/hour as the expected delay cost and 34% selected 751 - 1000 NOK/hour. These were the most answered cost intervals. We further assume 230 working days per year. The mandatory break time (M) is set to 0.75 hours each day since truck drivers are required to have a 45 minutes rest after driving for 4.5 hours. Refueling time (RT) depends on the necessary fraction of public high-speed charging during the day, as stated in Table 5.2. The refueling time and mandatory break time for the transport types can be found in Table 5.7.

Table 5.7: Mandatory break time and refueling time for different transport types. The unit is hours/day.

Transport type	**Mandatory break (M)**	**Refueling time (RT)**
Short-haul	0.75	0.3
Mixed	0.75	0.8
Long-haul	0.75	1.4

The station availability (StA) parameter is a constant that is multiplied by the refueling time. The purpose of this is to differentiate between different stages of development and the impact that particular stage has on trucking companies of various sizes doing different transportation distances. As values, we use the range 1-5, where a lower weight corresponds to better availability. Each stage of development corresponds to a set of StA parameters for short-haul, long-haul, and mixed transportation and for small, medium, and large-sized companies. These can be found in Table 5.8.

Table 5.8: Station availability (StA) parameters used for each stage of development. The scale is from 1-5.

		Small	**Medium**	**Large**
Stage 1	Short-haul	3	3	3
	Long-haul	5	5	5
	Mixed	5	4	3
Stage 2	Short-haul	2	2	2
	Long-haul	3	3	3
	Mixed	3	2.5	2
Stage 3	Short-haul	1	1	1
	Long-haul	1	1	1
	Mixed	1	1	1

For stage 1, StA is set to 3 for all companies doing short-haul transportation and 5 for all companies doing long-haul transportation. In this stage, there are only charging stations around major-freight terminals. This means vehicles must return to that base to charge during the day. This is not sustainable for long-haul transportation, and StA is set to the maximum value of 5. For short-haul transportation, this could be suitable if they operate around these particular terminals but not if they operate in remote areas or areas without terminals. StA is therefore set to 3. For companies doing mixed transportation, StA is higher for smaller companies. It is set to 3 for large companies, 4 for medium companies, and 5 for small companies. When looking at the investment decision for medium or large-sized companies doing mixed transportation, it is important to note that for the results to be valid, they must not replace their entire fleet. This is because it is a central assumption that they can switch between BETs and DTs depending on the availability of public infrastructure. Smaller companies doing mixed transportation will usually not have this opportunity and lose the opportunity to take on long-haul assignments. The StA parameter is, therefore, the same for small companies doing long-haul and mixed transportation.

In stage 2, the same trend continues. Stage 2 includes development around large cities and major destinations, and StA is lower in all cases. For short-haul transport, it is set to 2. Finding a charging station during the day will be easier because there are more of them, but operating in remote areas is still difficult. For long-haul, it is set to 3 because there might only be specific long-distance routes that can provide accessible charging stations along the road. For mixed transportation in stage 2, the values are justified by the same argumentation as in stage 1. In stage 3, there are also available charging stations in remote areas. StA is therefore set to 1, and there is no additional penalty cost due to the lack of charging facilities.

The scenarios *slow development*, *base*, and *rapid development* represent cases in which the government subsidizes 20%, 50%, and 80% of the infrastructure development costs. Each stage's deployment time in the scenarios is adjusted to our predictions for the development in Norway. This is shown in Table 5.9. In all scenarios, stage 1 is present from 2023 to 2025 since this is the stage we are currently in. In the base scenario, charging stations for heavy-duty transport is built to have sufficient infrastructure in remote areas within ten years. Norway aims for half of all new heavy-duty trucks to be zero emission in 2030 and to reach this goal, more infrastructure must be in place. Therefore, infrastructure build-out will likely be a greater focus area in the coming years. However, due to technological limitations and necessary power grid reinforcements, it might happen some years later than 2030. The rapid build-out scenario includes charging infrastructure as a priority area as soon as possible. We assume that stage 3 can be reached within 2028 if this is made a greater area of priority. The slow build-out scenario is one where stage 3 is not reached until 2038. There is some build-out around major freight terminals and cities during the next 15 years, but there is a lack of charging stations in remote areas. This could be due to other technologies, such as hydrogen, being prioritized, power grid reinforcements being expensive and difficult, or a lack of political initiatives to invest in the necessary infrastructure.

Table 5.9: Infrastructure scenarios.

	Stage		
Year	Slow	Base	Rapid
2023	1	1	1
2024	1	1	1
2025	1	1	1
2026	1	1	2
2027	1	2	2
2028	2	2	3
2029	2	2	3
2030	2	2	3
2031	2	2	3
2032	2	2	3
2033	2	3	3
2034	2	3	3
2035	2	3	3
2036	2	3	3
2037	2	3	3
2038	3	3	3
2039	3	3	3
2040	3	3	3

5.2.4 Toll and Ferry

Toll and ferry costs are specific to the transport route and vary with each transport assignment. Table 5.10 shows the roundtrip toll and ferry cost for selected routes in Norway, based on Fremtind (2023). BETs currently get 50-100% toll station discount (Autopass, 2023), and for all routes in Table 5.10, the current discount is 100 % for BETs. However, in the national budget for 2023, the government stated that the maximum price toll price for electric vehicles should be 70% instead of 50% (Loftås, 2022). Additionally, the Norwegian Public Roads Administration recommends removing the toll advantage for electric vehicles in 2025 (NAF, 2022). Therefore, we set toll costs for BETs to 20% of DTs. We multiply the average cost per km for toll and ferry for BETs and DTs by the annual driving distance to obtain the yearly toll costs.

Table 5.10: Toll and ferry costs for selected distances. Numbers are collected from Fremtind (2023), assuming a truck with length 10.01 - 12.5m and weight above 3.5 tons.

Route	**Distance (km)**	**Toll (NOK)**		**Ferry (NOK)**		**Toll & Ferry per km (NOK/km)**	
		BET[1]	**DT**	**BET**	**DT**	**BET**	**DT**
Bergen - Trondheim - Bergen	1394	252	1261	392	784	*0.46*	*1.47*
Oslo - Trondheim - Oslo	984	349	1744	0	0	*0.35*	*1.77*
Oslo - Stavanger - Oslo	1096	239	1194	0	0	*0.22*	*1.09*
Narvik - Tromsø - Narvik	464	100	498	0	0	*0.21*	*1.07*
Trondheim - Namsos - Trondheim	388	126	628	0	0	*0.32*	*1.62*
Namsos - Narvik - Namsos	1490	160	802	479	958	*0.43*	*1.18*
Average per km						***0.33***	***1.37***

1) BETs currently pay 0% in tolls, but a rate of 20% is assumed in this table.

5.2.5 Maintenance and Other Variable Costs

Lower maintenance costs are usually associated with BETs, as explained in Section 2.4.2. We set maintenance costs as a rate per km and use a rate of 1.0 NOK/km for BETs and 1.5 NOK/km for DTs. This is based on personal communication with Frode Rømo in Sintef Industry (01.11.22). Other variable costs are related to keeping the truck in operation, including washing, administration, tires, and other items. In Figenbaum et al. (2019), this component adds up to 2 NOK/km for BETs and 2.5 NOK/km for DTs when maintenance is included. We deduct the estimated maintenance cost from these values and end up with other variable costs equal to 1.0 NOK/km for BETs and DTs. Both the maintenance rate and other variable cost rate is multiplied by the annual driving distance to obtain the annual costs.

5.3 Discount Rate

Operational costs and the residual value are discounted back to the investment year. Our literature study shows that a discount rate between 6% and 7% is commonly used for this TCO analysis. However, Miljødirektoratet (2020) uses 9.5% as the discount rate for the road transport sector. We also asked NLF members which discount rate they use when considering new investments. Of the respondents, more than 50 % answered that they either do not know or that it is not relevant. Of the respondents who gave a discount rate, 25% answered *less than 5%*, 52% answered *between 5.1 and 7.0%*, and 15 % answered *between 7.1 and 9.0%*. The remaining 8% use *above 9.1 %* as the discount rate. Based on these findings, we choose a discount rate of 7.5%.

We do not discount costs further back than the investment year. This is because the objective is to compare TCOs for different investment years. If all costs are discounted back to the current time, the later investment will always appear less expensive. We assume truck owners cannot delay investment since they need trucks to operate their businesses. Therefore this type of discounting is not relevant to the decision-making process. Instead, we want to show how the TCO for BETs develops over the years.

5.4 Stock-Flow Modeling

Based on responses from our survey to NLF members, we assume that 25% of trucking companies invest in BETs rather than DTs the year after BETs have a lower TCO than DTs. In the following years, we estimate that it takes 5 years before 100% of the companies within the given segment invest in BETs rather than DTs. The increase from 25% to 100% is assumed linear. We consider a case where each transport distance represents a third of the truck fleet and assume that the company size is medium.

The slow, base, and rapid infrastructure scenarios, defined in Table 5.9, are connected to cases where the government subsidizes 20%, 50%, and 80% of the infrastructure development costs. According to NTP, transportation of goods on the road is expected to increase by 29% by 2050, and half of this growth will occur before 2030 (Regjeringen, 2021b). We assume that the national truck fleet of 68 500 trucks (SSB, 2022a) grows accordingly. We further estimate that 9% of the fleet is replaced each year, which is based on data from SSB (2022a) and OFV (2023). This replacement rate corresponds to a longer holding period than 7 years, which is realistic as trucks are often resold and used for other applications before they are sold to other countries or scrapped. We assume that the national truck fleet only consists of BETs and DTs and that trucking companies invest in either of these technologies.

Thema Consulting (2022) estimates that the cost of building out infrastructure in Norway for the existing truck fleet is approximately 12.9 BNOK when not considering area costs. We adjust this amount for the expected increase in truck volumes, and end up with a total cost of around 15.3 BNOK. Of these investments, we assume that around 5 BNOK has happened when stage 2 is reached.

5.5 Summary of Deterministic Parameters

Table 5.11 summarizes the deterministic parameters that are not company specific and which are used in the TCO calculations.

Table 5.11: Deterministic parameters.

	BET	**DT**
Maintenance costs ($C_t^{\text{Maintenance}}$)	1.0 NOK/km	1.5 NOK/km
Other operational costs (C_t^{Other})	1.0 NOK/km	1.0 NOK/km
Toll costs (C_t^{Toll})	0.3 NOK/km	1.4 NOK/km
Waiting cost (C_t^{Wait})	750 NOK/hour	-
Battery size (Cap_t^{BET})	540 kWh	-
Energy consumption (E)	1.7 liter/km	0.4 kWh/km
Mandatory break time (M)	0.75 hours	-
Lifetime of truck (N)	7 years	7 years
Operational days per year (O)	230	230
Residual value rate (α)	20%	20%
Investment support rate (β)	40%	-
Gross profit petrol stations (γ)	-	10%
Discount rate (ρ)	7.5 %	7.5 %

Chapter 6

Results

In this chapter, we present the resulting TCOs and discuss when it is more cost-efficient for companies to invest in BETs rather than DTs. We begin by analyzing the results for different combinations of input parameters in Section 6.1. Then, in Section 6.2, we perform a sensitivity analysis to explore how vulnerable the results are to parameter changes. Section 6.3 investigates how different governmental support schemes affect the TCO. In Section 6.4, we calculate what these support schemes will cost the government and make a comparison to find the most effective one.

All TCO analyses are performed using 20 000 Monte Carlo simulations implemented in Python, and the source code can be found in Krüger and Thiis (2023). Each round of simulations is for a specific investment year and has a run-time of approximately 0.8 seconds. The result of one simulation is a list of 20 000 potential TCOs, split by cost type, which are used for further analysis of the results. We mainly look at the expected value of the TCO, but we also compare the standard deviation, confidence intervals, and maximum and minimum values to explore the variability. Unless otherwise stated, we look at a medium-sized company that operates in the mixed transport segment and has a charger at the company property or the driver's home. The base case for infrastructure development is assumed.

6.1 TCO Analysis

The decision for a company to invest in a BET rather than a DT depends on the transport distance, company size, and speed of infrastructure development. We, therefore, analyze how the TCO changes under different combinations of these parameters. First, we compare the TCO for BETs and DTs for different transport distances. Next, we explore how the level of infrastructure development affects the TCOs of the two technologies and compare companies of various sizes. We then visualize the cost structure to understand the cost drivers and compare the development for both BETs and DTs. Finally, we summarize the findings across multiple dimensions.

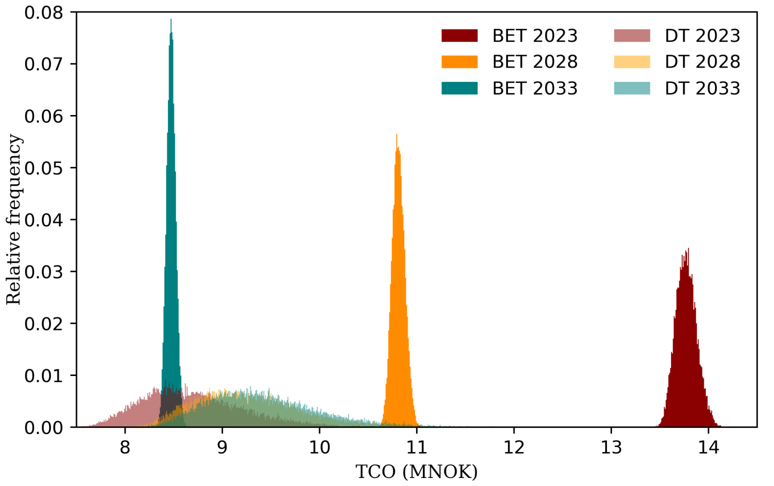
6.1.1 Transport Distance

The optimal investment year in BETs varies with the transport distance. Figure 6.1 compares the relative frequencies of TCOs in 2023, 2028, and 2033 for short-haul, long-haul, and mixed transportation. Histograms display the relative frequencies of the TCOs for BETs and DTs. A histogram towards the left indicates a lower expected TCO, and the histogram's width shows the variability. Descriptive statistics are shown in Table 6.1.

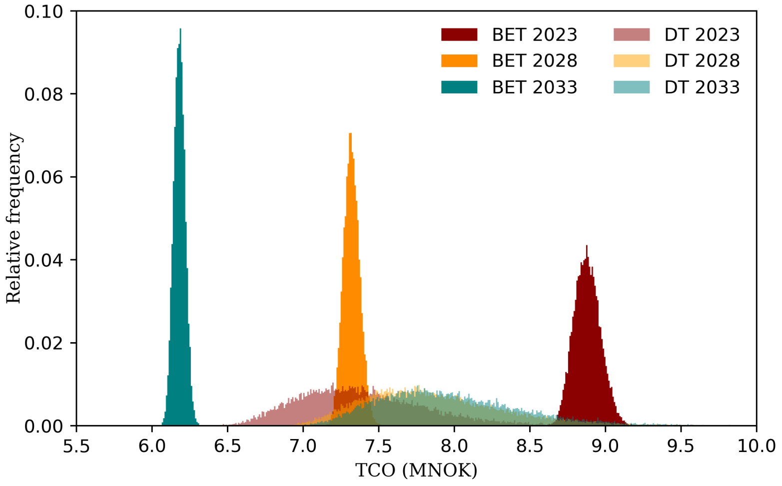
Table 6.1: Descriptive statistics of TCO distributions for short-haul, mixed, and long-haul transport.

Technology	Investment year	Mean	Median	Max	Min	St. Dev.
		(MNOK)				
		Short-haul				
BET	2023	5.25	5.25	5.50	5.03	0.07
	2028	4.66	4.65	4.80	4.53	0.04
	2033	4.42	4.42	4.53	4.32	0.03
DT	2023	6.08	6.05	7.99	5.32	0.32
	2028	6.42	6.38	8.58	5.68	0.35
	2033	6.52	6.47	8.70	5.70	0.35
		Mixed				
BET	2023	8.88	8.88	9.21	8.57	0.09
	2028	7.32	7.32	7.54	7.14	0.05
	2033	6.18	6.18	6.35	6.05	0.04
DT	2023	7.39	7.34	9.76	6.37	0.43
	2028	7.85	7.79	10.29	6.72	0.46
	2033	7.97	7.91	10.76	6.88	0.47
		Long-haul				
BET	2023	13.77	13.77	14.19	13.40	0.11
	2028	10.81	10.81	11.05	10.60	0.07
	2033	8.47	8.47	8.67	8.31	0.05
DT	2023	8.70	8.64	11.87	7.42	0.53
	2028	9.27	9.20	12.87	8.02	0.58
	2033	9.42	9.35	13.07	8.06	0.59

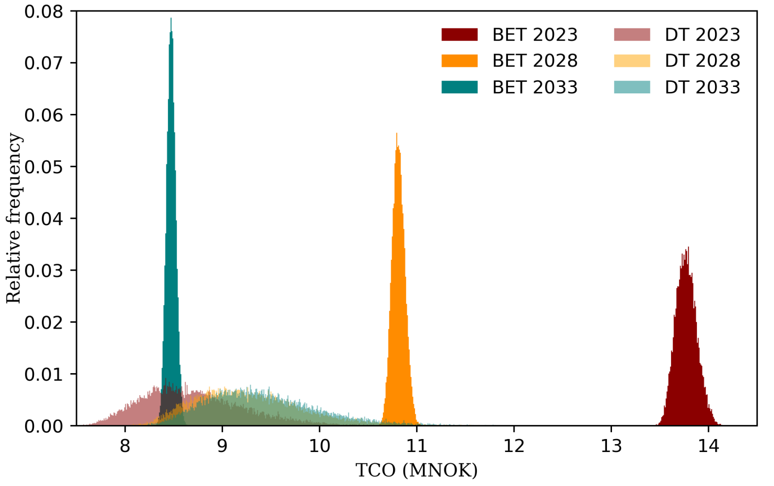
The results for the short-haul segment are shown in Figure 6.1a. We see that in 2023, BETs are already the preferred option. This is due to a lower expected value and standard deviation than DTs. In 2023, BETs have an expected value of about 5.25 MNOK and a standard deviation of 70 KNOK. For DTs, the expected value is 6.08 MNOK, and the standard deviation is 320 KNOK. We also observe that the difference between maximum and minimum values is significantly higher for DTs than for BETs. In 2028 and 2033, the BET distribution shifts further to the left, indicating that BETs are an even better option in the future. On the other hand, the expected value and standard deviation increase for DTs.



(a) **Short-Haul**



(b) **Mixed**



(c) **Long-haul**

Figure 6.1: Comparison of relative frequencies of TCOs for BETs and DTs. Transport segments considered are short-haul, mixed, and long-haul in 2023, 2028, and 2033.

Figure 6.1b shows the results for BETs and DTs doing mixed transportation. Table 6.1 show that the expected value in 2023 is 8.88 MNOK for BETs, which is higher than the expected value for DTs of 7.39 MNOK. We further see that the distributions overlap in 2028, meaning BETs are competitive with DTs. In 2033, BETs will be significantly better than DTs. BETs have a lower standard deviation than DTs all years, indicating more uncertainty related to DTs. For long-haul transportation, presented in Figure 6.1c, we observe that DTs are the optimal choice in both 2023 and 2028. It is only by 2033 that BETs become cost-competitive with DTs.

6.1.2 Infrastructure Development Scenarios

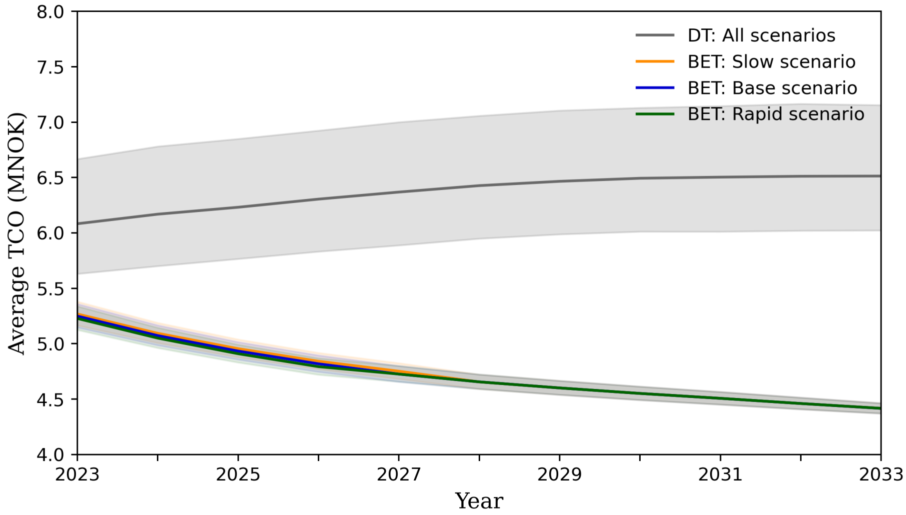
Infrastructure for public high-speed charging is essential when operating BETs over longer distances, as the battery range is insufficient for driving an entire day without charging. We, therefore, explore how different rates for the development of charging infrastructure affect the TCO. We consider the infrastructure scenarios *slow*, *base*, and *rapid*. Table 6.2 presents the year BETs are cost-competitive with DTs for the different transport distances and development scenarios.

Table 6.2: Optimal investment year in BETs under different infrastructure development scenarios. The optimal investment year is the year that the TCO is lower for BETs than DTs.

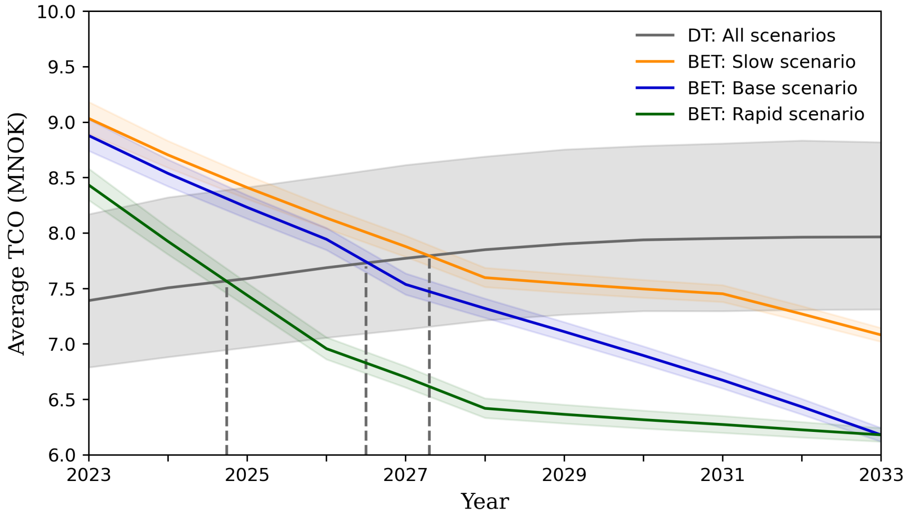
Transport distance	**Infrastructure scenario**		
	Slow	**Base**	**Rapid**
Short-haul	2023	2023	2023
Mixed	2028	2027	2025
Long-haul	2036	2032	2028

For short-haul, BETs are already cost-competitive, independent of the scenario. In the slow scenario, BETS are not cost-competitive until 2028 for mixed transportation and 2036 for long-haul transportation. In the rapid scenario, BETs are cost-competitive in 2025 for mixed transportation and in 2028 for long-haul.

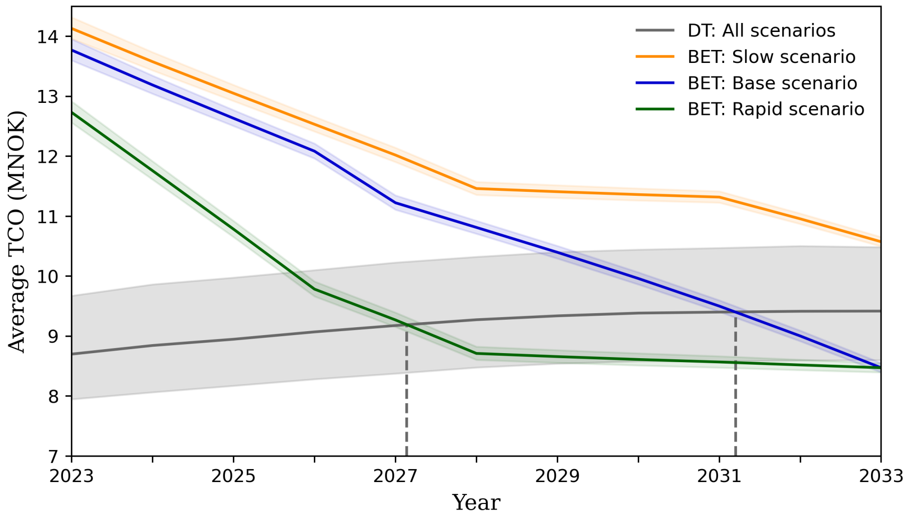
Figure 6.2 presents the development of average TCOs over time for three different development scenarios and transport distances. The figure displays 90%-confidence intervals as shaded areas around the lines, which visualizes the range of values that the TCO is likely to take. We observe that BETs have much smaller confidence intervals than DTs, regardless of the infrastructure development scenario and transport segment. We, therefore, anticipate the TCO for BETs to be closer to its expected value than the TCO for DTs. For short-haul transportation (Figure 6.2a), it is clear that the infrastructure scenario is of little importance. Given the shorter driving distances, the trucks mostly charge off-shift and are not significantly affected by a limited supply of high-speed chargers. As a result, the TCO for BETs is already below that of DTs, and the cost difference is increasing over the years. For mixed transport (Figure 6.2b), we observe more overlap between the confidence intervals for BETs and DTs in all scenarios. This means that the TCOs for the two technologies could be similar during these years. For long-haul transportation (Figure 6.2c), it takes longer before the expected TCO for BETs is in the 90% confidence interval of DTs, especially in the slow scenario. The rate at which infrastructural development occurs is thus an important factor in when BETs become cost-competitive.



(a) Short-haul



(b) Mixed

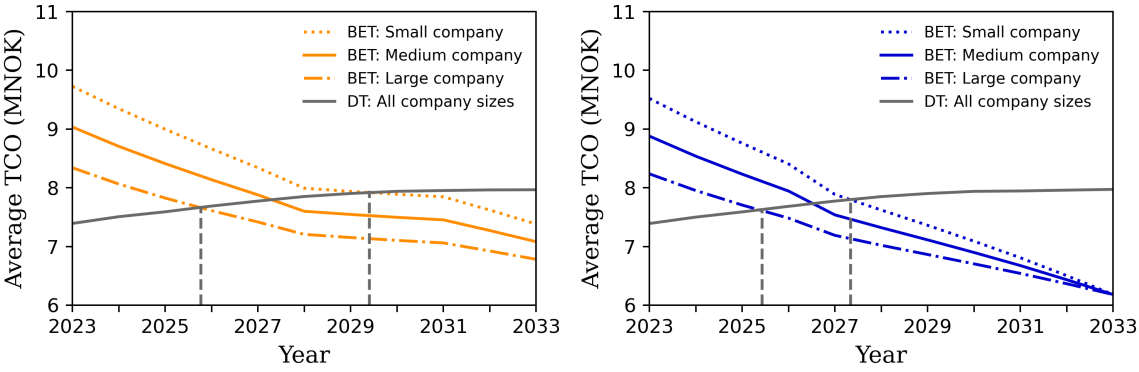


(c) Long-haul

Figure 6.2: TCO development for slow, base, and rapid infrastructure development in short-haul, mixed, and long-haul transport. The shaded areas represent a 90 % confidence interval.

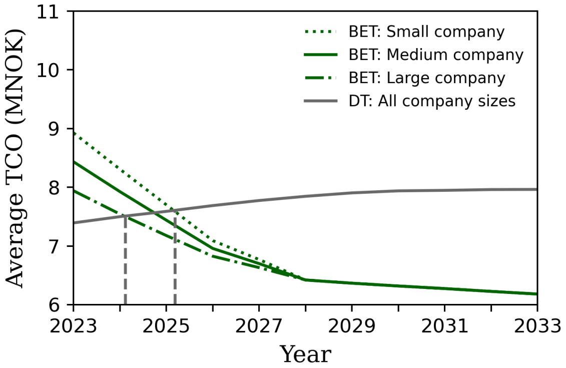
6.1.3 Company Size

TCOs for BETs can differ for companies of different sizes, even though the infrastructure and transport distance is the same. The difference becomes visible when companies engage in mixed transportation, as possessing a larger truck fleet provides more flexibility to assign BETs to appropriate transport routes. Figure 6.3 compares the TCOs for BETs and DTs doing mixed transportation across company sizes in three scenarios for infrastructure development.



(a) Slow development

(b) Base development



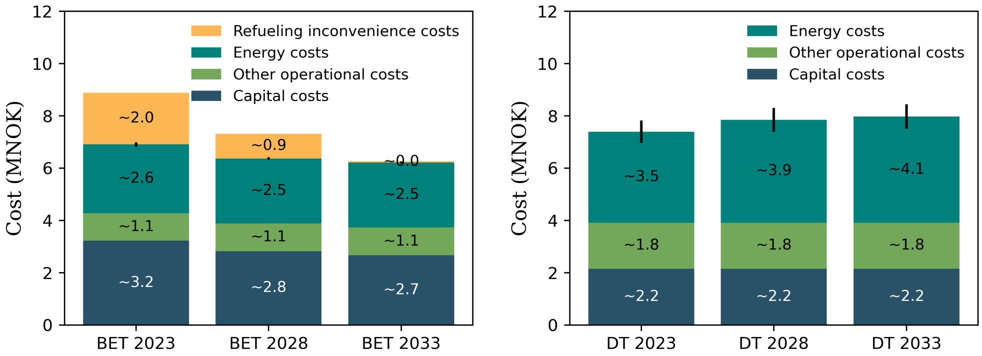
(c) Rapid development

Figure 6.3: Development of average TCO doing mixed haul transportation for different company sizes. The figures show different scenarios of infrastructure development.

Smaller companies have a higher TCO than larger ones within the same infrastructure development speed. In the slow development scenario (Figure 6.3a), the difference between company sizes is the largest. Here, BETs become cost-competitive with DTs 3-4 years earlier for large companies than for small companies. For the base scenario of infrastructure development (Figure 6.3b), BETs become cost-competitive with DTs between 2025 and 2026, which is about two years earlier than for small companies. In the rapid scenario (Figure 6.3c), company size is of less importance, and the TCOs for BETs and DTs are about the same around 2024 and 2025.

6.1.4 Cost Structure

The cost structure provides insight into what causes the cost differences between BETs and DTs. This can contribute to highlighting the actions that must be taken to make BETs competitive with DTs for mixed and long-haul transport. Figure 6.4 shows the cost structure for the expected TCO for BETs and DTs doing mixed transportation in 2023, 2028, and 2033.



(a) BET

(b) DT

Figure 6.4: Development of average TCO for BETs and DTs by cost component in 2023, 2028, and 2033. The black bar shows the standard deviation of energy costs.

We observe that for BETs, the refueling inconvenience cost decreases from 2.0 MNOK in 2023 to 0.9 MNOK in 2028 and is zero in 2033. As more infrastructure is established over the years, the refueling inconvenience cost is reduced and eventually disappears. Energy costs are stable at around 2.5 MNOK. Moreover, capital costs for BETs are expected to decrease from 3.2 MNOK in 2023 to 2.8 MNOK in 2028 and 2.7 MNOK in 2033. The decrease in capital costs is more significant initially due to the exponentially decaying learning function. For DTs, there is a slight increase in TCO over the years, caused by increasing diesel costs from 3.5 MNOK in 2023 to 4.1 MNOK in 2033. Capital costs are stable at 2.2 MNOK, and refueling inconvenience costs are non-existent. Figure 6.4 further shows that BETs have a lower standard deviation in energy costs than DTs, illustrated by the black bar in the figure. BETs also have lower other operational costs than DTs, mainly due to lower maintenance and toll rates. This component is 1.1 MNOK for BETs and 1.8 MNOK for DTs and is the same in each observation year.

The results show that refueling inconvenience is the main contributor to the cost reductions for BETs over the years. However, refueling inconvenience costs are specific to the type of transport distance. Figure 6.5 therefore shows the refueling inconvenience costs across transport distances. We observe that the refueling inconvenience cost is already zero for short-haul segments in 2023, whereas for mixed and long-haul transport, it represents a significant amount of the total costs.

6.1.5 Summary of expected TCOs

An overview of the presented results is shown in Table 6.3. Three years are displayed, and the results are divided by transport distance, company size, and infrastructure build-out scenario. Bold numbers represent the instances where the expected TCO for BETs is less than for DTs.

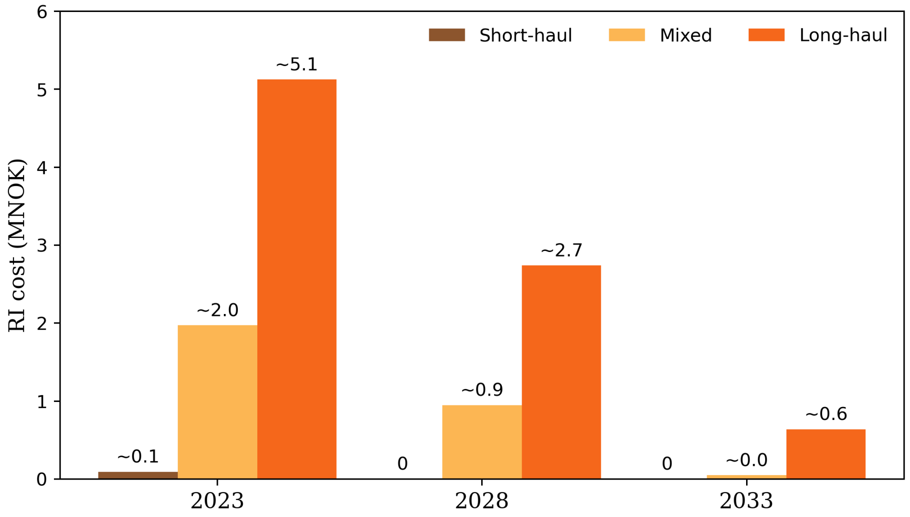


Figure 6.5: Development of average refueling inconvenience cost (RI cost) grouped by transport segment.

Table 6.3: Expected TCO (in MNOK) for BETs and DTs for different development scenarios, transport segments, and business sizes. Bold font indicates that BETs have a lower TCO than DTs within the given scenario, transport distance, and company size. Abbreviations: SB = Small Businesses, MB = Medium Businesses, LB = Large Businesses.

		Short-haul			Mixed			Long-haul		
		SB	MB	LB	SB	MB	LB	SB	MB	LB
Investment year = 2023										
	Rapid development	**5.23**	**5.23**	**5.23**	8.93	8.43	7.94	12.73	12.73	12.73
BET	Base development	**5.25**	**5.25**	**5.25**	9.52	8.88	8.24	13.77	13.77	13.77
	Slow development	**5.27**	**5.27**	**5.27**	9.73	9.03	8.34	14.13	14.13	14.13
DT	All scenarios		6.09			7.39			8.71	
Investment year = 2028										
	Rapid development	**4.66**	**4.66**	**4.66**	**6.42**	**6.42**	**6.42**	**8.71**	**8.71**	**8.71**
BET	Base development	**4.66**	**4.66**	**4.66**	**7.62**	**7.32**	**7.02**	10.81	10.81	10.81
	Slow development	**4.66**	**4.66**	**4.66**	7.99	**7.60**	**7.21**	11.46	11.46	11.46
DT	All scenarios		6.42			7.85			9.27	
Investment year = 2033										
	Rapid development	**4.42**	**4.42**	**4.42**	**6.18**	**6.18**	**6.18**	**8.47**	**8.47**	**8.47**
BET	Base development	**4.42**	**4.42**	**4.42**	**6.18**	**6.18**	**6.18**	**8.47**	**8.47**	**8.47**
	Slow development	**4.42**	**4.42**	**4.42**	**7.38**	**7.08**	**6.78**	10.57	10.57	10.57
DT	All scenarios		6.52			7.96			9.42	

6.2 Sensitivity Analysis

This section explores how the TCO changes when the input parameters change. First, we show an overview of the increase in TCO when individual input parameters are increased by the same amount. We then discuss how the waiting cost and station availability affect the investment decision. Lastly, we discuss the cost differences when at-home charging is unavailable and the effect that has on the TCO.

6.2.1 Increasing Input Parameters by 33%

The TCO calculation consists of a substantial number of input parameters that affect the results to various amounts. Many of these parameters were assumed constant but could be subject to changes in the future. We, therefore, explore the effect the choice of these input values has on the TCO and the investment decision. This can be used to highlight areas of further research and, in future cost estimations, put focus on the input parameters that affect the results the most. Figure 6.6 shows how much (in %) the TCO in 2023 increases from the base case when each input parameter is increased by 33% while the others are kept constant.

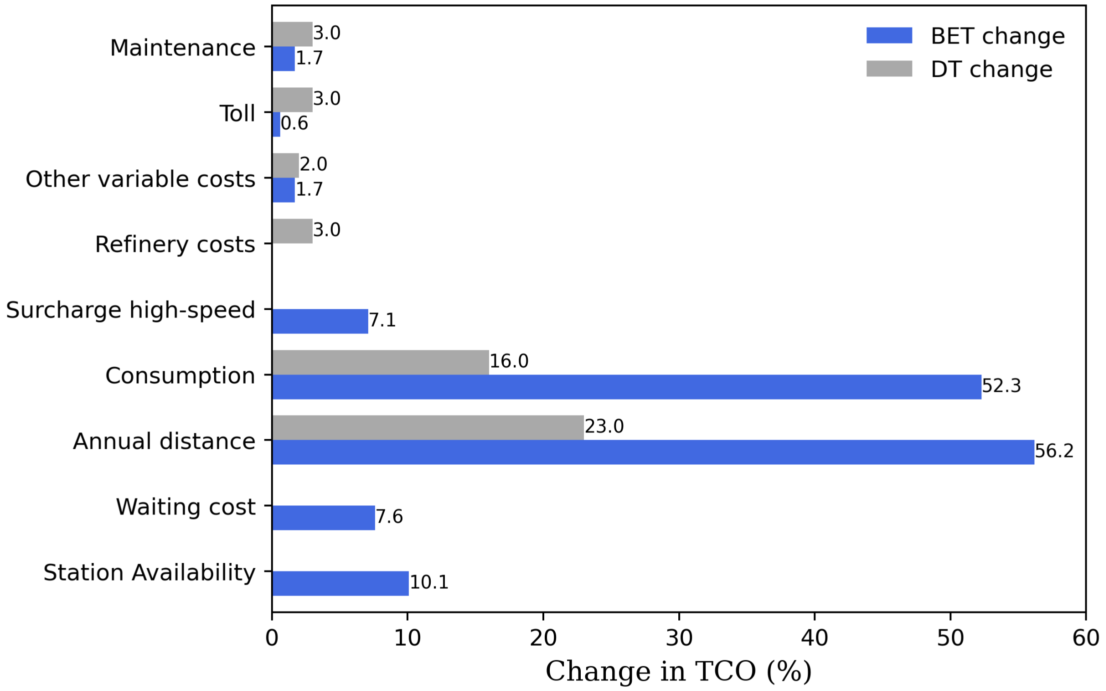


Figure 6.6: Change in TCO in 2023 when each input parameter is increased by 33%.

We observe that increasing the maintenance rate, toll rate, and other variable costs has a marginal effect on the final TCO. This is due to *other operational costs* only being a small part of total costs. Since these parameters are set as a rate per km and are all assumed higher for DTs, increasing them leads to a slightly higher TCO increase for DTs than BETs. Furthermore, increasing the refinery costs increases the TCO for DTs to a limited extent and will not affect BETs. This suggests that keeping the refinery costs constant in our model does not affect the results significantly. Increasing the surcharge for high-speed charging has a relatively significant effect on the final TCOs for BETs, which is because the surcharge accounts for 70 - 90% of the total high-speed charging costs at public charging stations. The input parameters that stand out in Figure 6.6 are the consumption rate and annual distance. Increasing the consumption increases the daily energy usage by the same fraction, meaning that the energy costs increase. Additionally, it increases the time required for high-speed charging during the day, which affects the BET costs. Since the penalty cost for using high-speed charging is relatively high initially due to a lack of public infrastructure, this also increases the refueling inconvenience. This explains why the consumption increase affects the TCO for BETs more than DTs. The same goes for increasing the annual distance. Increased driving distance puts a higher energy requirement for both BETs and DTs. In addition, it affects the high-speed charging time and refueling inconvenience for BETs, which increases BET costs even further. The last two parameters increased are the waiting cost and station availability, which are only relevant for BETs. These affect the cost of refueling inconvenience considerably. Due to the uncertainty tied to these values, the following subsections will go through these in more detail.

6.2.2 Changing the Waiting Cost

In the survey sent out to NLF members, we asked them to estimate the hourly cost if the transport was delayed. Based on the majority of the answers, we set the hourly waiting cost to 750 NOK/hour. However, the survey showed that the estimated cost varies across companies. Figure 6.7 illustrates what happens to the TCO for different waiting cost values for a medium-sized company doing mixed-haul transportation in the base scenario for infrastructure development.

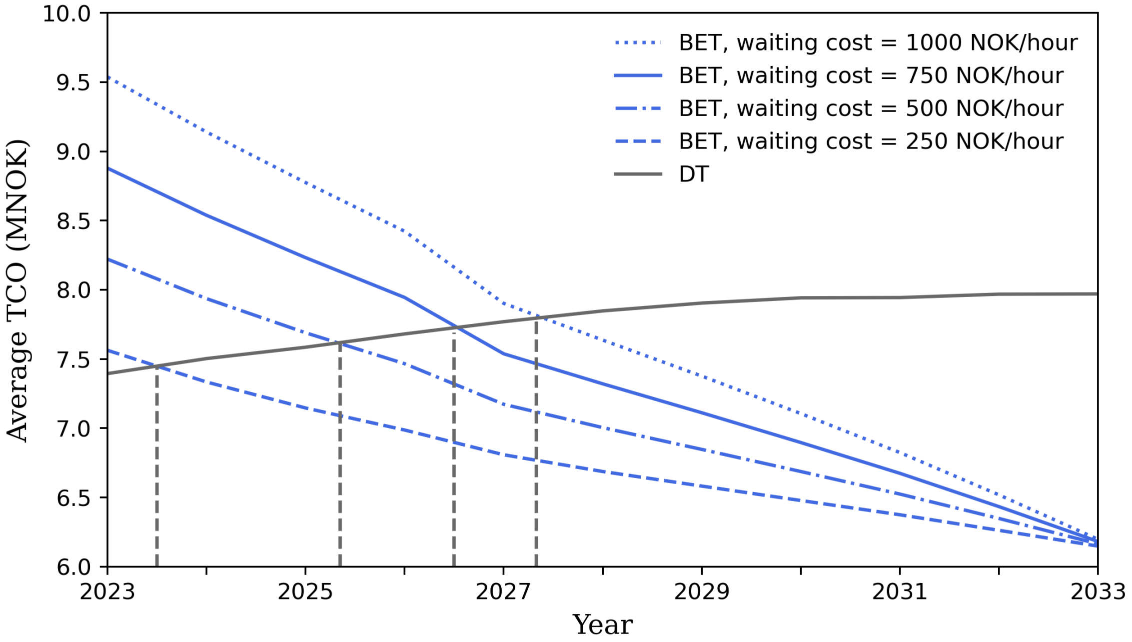


Figure 6.7: Expected TCO from 2023 to 2033 for different waiting cost levels, compared to the TCO for a DT.

For companies with a low waiting cost of 250 NOK/hour, BETs will become cost-competitive between 2023 and 2024. For companies with a high waiting cost of 1000 NOK/hour, this will not happen until 2027-2028. This shows that the investment decision and timing vary across companies. Furthermore, the effect of the waiting cost is reduced over time. In 2033, the waiting cost level is identical. This is due to the assumption that infrastructure will be fully built out in 2033 in the base scenario. After this, the refueling inconvenience will be zero, making the waiting cost irrelevant.

6.2.3 Varying Station Availability

The station availability (StA) parameter ranges from 1-5 and indicates the available amount of charging facilities and the effect that has on a company with given specifications. Figure 6.8 shows how the TCO for a medium-sized company doing mixed-haul transportation changes over the years when StA is set at different levels.

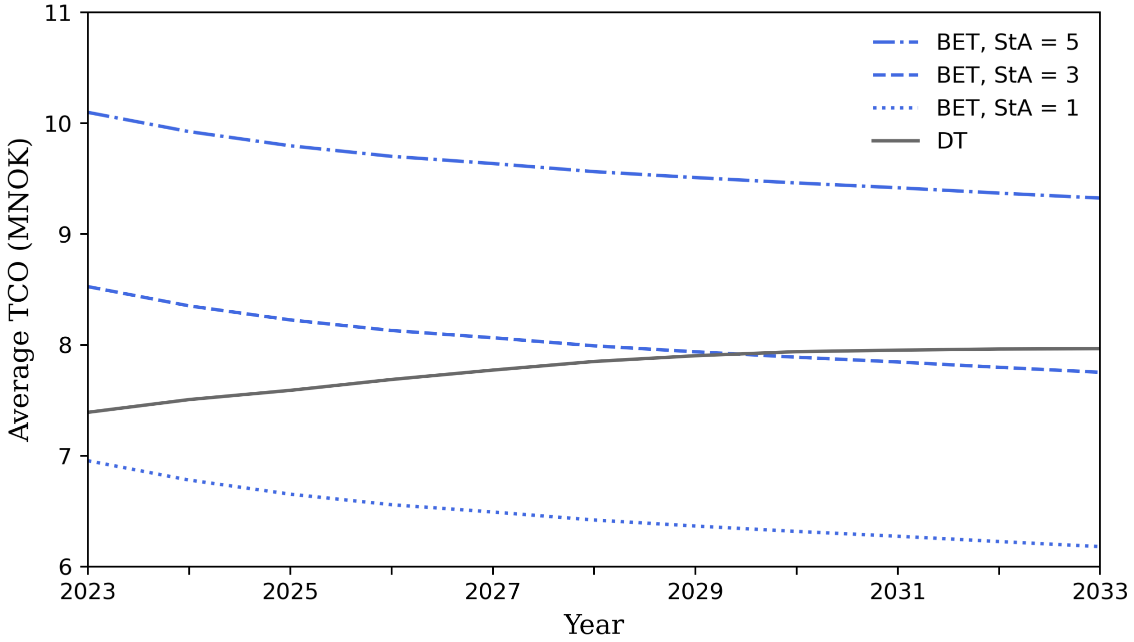


Figure 6.8: Expected TCO from 2023 to 2033 for three different levels of StA, compared to the TCO for a DT.

The choice of station availability parameter shifts the distribution. When StA is increased from 3 to 5, the resulting TCO is increased by 1.5 MNOK. When StA is decreased to 1, the TCO is decreased by 1.5 MNOK. We can see from the figure that if there is full availability of charging stations, i.e. StA = 1, then it would be beneficial to invest in BETs between 2023 and 2024. When StA = 1, the refueling inconvenience is zero, and there is no difference between companies of different sizes driving short, mixed, or long-haul. This shows that the model is highly sensitive to the input values for StA. In our model, we used a decreasing StA in all scenarios, which is a determining factor for the shape of the development. As StA is multiplied by the refueling time and waiting cost, it increases the refueling inconvenience significantly. This highlights the importance of increasing the availability of charging stations to avoid high refueling inconvenience costs.

6.2.4 Private vs. Public Charging

We assumed that trucking companies have a charger on the company property or at the driver's home, known as at-home sharing. However, this might not be the case for all companies. Our survey of the truck drivers indicated that 15% of the trucks are parked at 24-hour rest stops, rest areas, or other places along the route at night. This might apply to companies doing long-haul transportation where an overnight layover is required. The survey also indicated that 10% of the trucks are parked at the customer, loading and unloading area or terminal. For these types of companies, it might not be possible to use their own charging facilities, and they would therefore have to use public charging stations. This will increase energy costs due to the surcharge. Table 6.4 shows the difference between at-home and public charging costs. The right column states the increase (in %) in charging costs if at-home charging is not available. As short-haul transportation relies more on at-home charging, the cost difference is much larger for this segment than for long-haul and mixed transportation.

Table 6.4: The difference between total charging costs for public slow charging and at-home charging across transport segments.

	At-home slow charging	Public slow charging	
	Avg. total charging cost (MNOK)		Increase
Short-haul	1.14	3.46	204%
Mixed	2.62	4.92	88%
Long-haul	4.10	6.39	56%

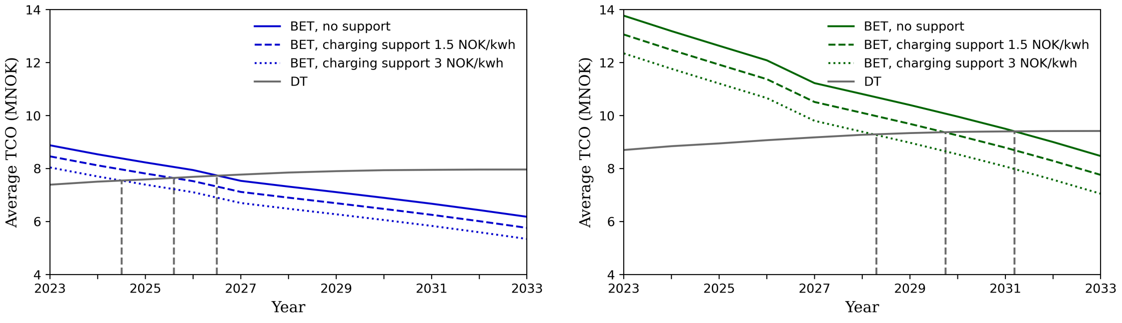
Since the energy costs for BETs are not expected to change significantly, this cost difference will continue for all years. For the investment timing, this will propagate and delay the optimal time of investments in BETs considerably. These results, therefore, show the importance of investing in private charging facilities for BETs, either located at the company's property or at the driver's home. If not, the energy costs will be much higher for BETs than for DTs.

6.3 Effects of Governmental Support

The government can help facilitate the transition to electric road freight. This section explores different support schemes, including charging support and increased investment support. We then compare these by calculating total cost reductions for a trucking company.

6.3.1 Charging Support Schemes

In our case study, we assume that charging stations add a surcharge of 6.49 NOK/kWh in addition to the electricity price. As the electricity price fluctuates between 0.1 - 2.55 NOK/kWh, this constitutes a large share of the energy costs for BETs. The government can help reduce BET costs by offering charging support to reduce charging costs. Figure 6.9 shows how the investment timing changes for different levels of charging support for a medium-sized company doing either mixed or long-haul transport. We look at government support rates of 1.5 and 3.0 NOK/kWh, which corresponds to a surcharge of 4.99 NOK/kWh and 3.49 NOK/kWh, respectively.



(a) Mixed transport

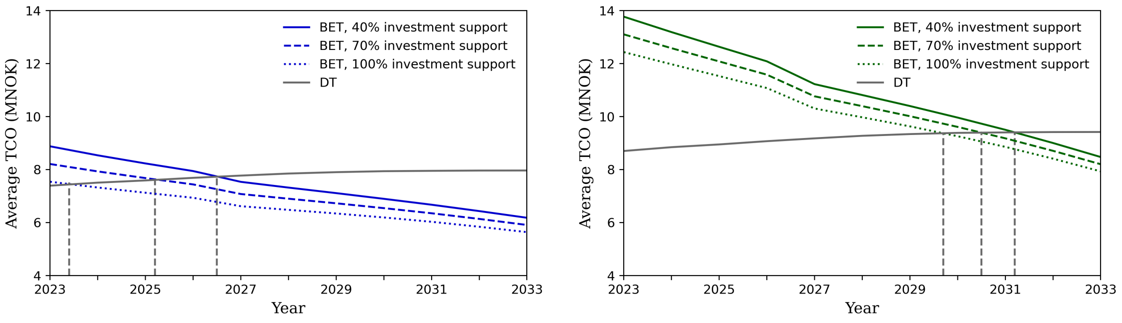
(b) Long-haul transport

Figure 6.9: Expected TCO from 2023 to 2033 when introducing charging support of 1.5 NOK/kWh or 3 NOK/kWh, compared to the TCO for a DT.

The results show that charging support of 3 NOK/kWh can accelerate the transition by 2 years for companies doing mixed transportation and by approximately 3 years for companies doing long-haul transportation. Charging support of 1.5 NOK/kWh can accelerate the transition by approximately 1 year for both segments.

6.3.2 Investment Support

The government currently grants 40% of the additional initial investment cost for BETs compared to DTs. Some argue that this should be increased to incentivize more investments. Figure 6.10 shows how the investment timing changes when the investment support is increased to 70% and 100%.



(a) Mixed transport

(b) Long-haul transport

Figure 6.10: Expected TCO from 2023 to 2033 when increasing the investment support level from 40% to 70% or 100%, compared to the TCO for a DT.

For companies doing mixed transportation, we observe that the investment timing changes when the investment support is increased. If the government grants 100% of the additional investment in BETs compared to DTs, it would be optimal to invest in BETs before 2024, whereas, with the current rate of 40%, it is not cost-competitive until 2026-2027. Investment support also reduces the TCO for long-haul transportation, but even with full investment support, investments are not optimal until around 2030. We further observe that the effect of government investment support decreases over time, which is plausible since BET investment costs are expected to decrease.

6.3.3 Comparison of Support Schemes

Introducing charging support schemes or additional investment support means a TCO reduction for the trucking companies that the government has to subsidize. Figure 6.11 shows the cost reduction for a company doing mixed transportation, which corresponds to the cost per truck for the government. The charging support is calculated based on the daily required energy (in kWh) at public charging stations multiplied by operational days per year and the lifetime of the truck.

The results show that increased investment support is the most cost-reducing measure during the first years. This is because capital costs are very high in the beginning. After 2026, providing charging support of 3.0 NOK/kWh will be the most cost-reducing measure as it will reduce the TCO by approximately 1 MNOK.

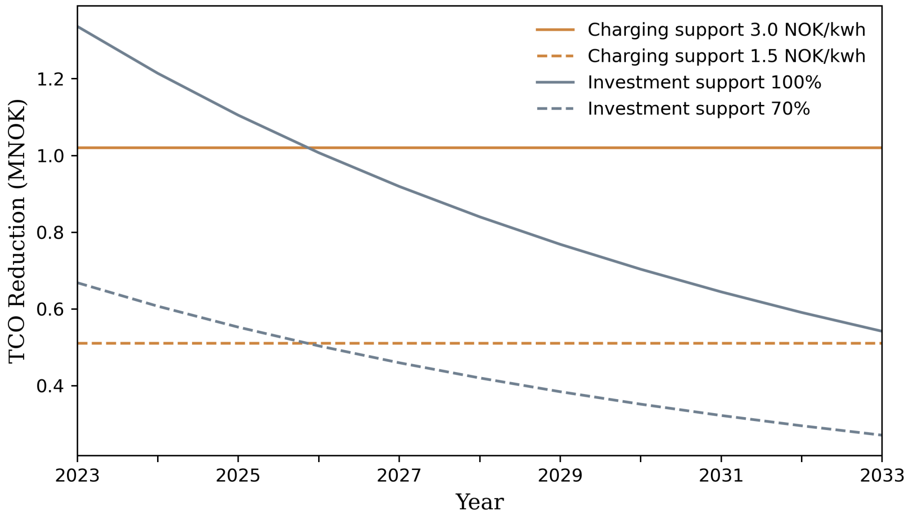


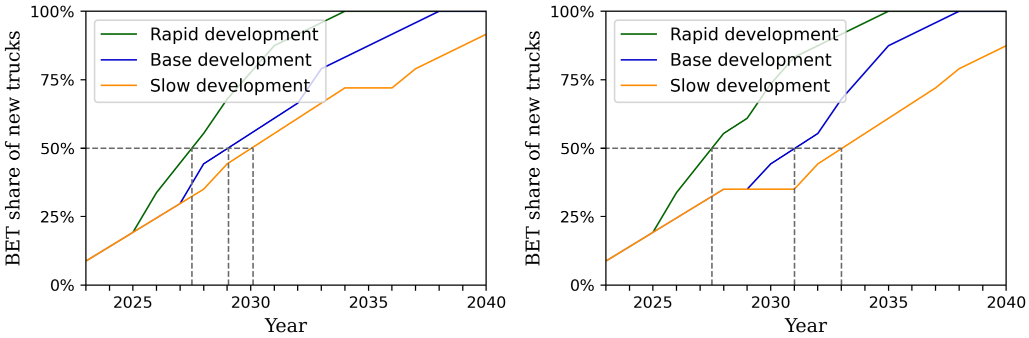
Figure 6.11: TCO reduction for a medium-sized company doing mixed transportation from 2023 to 2031 when introducing charging support or increasing the additional investment support.

6.4 Truck Fleet Development

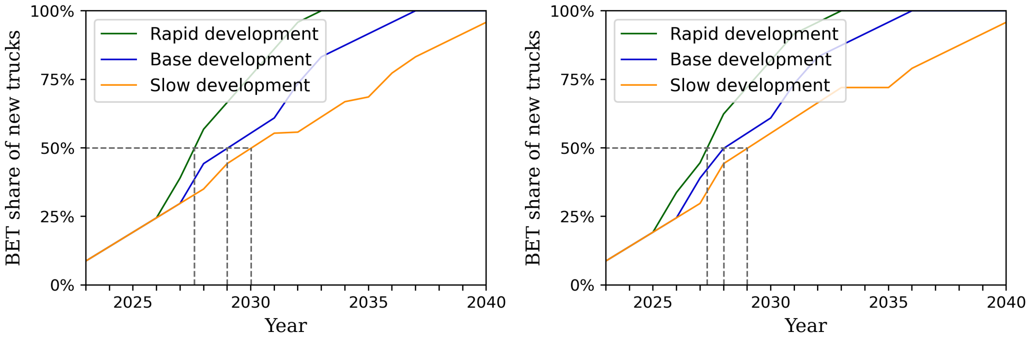
We develop a stock-flow model to explore how the truck fleet develops under different cases for government support. The results from the TCO analysis are used to make the investment decision. We explore four cases corresponding to different combinations of charging support and truck investment support from the government. These are presented in Table 6.5. In all cases, we consider the three scenarios for infrastructure development. The cases result in different speeds at which the truck fleet becomes battery-electric. The share of new BETs for each case in the different infrastructure scenarios is shown in Figure 6.12.

Table 6.5: Description of the four different cases of government support considered.

Support Case	**Description**
Case 1 (Existing support)	The existing investment support (40% of additional investment) is in place over the whole time period (2023 - 2040). No charging support.
Case 2 (Reduced support)	The existing investment support (40% of additional investment) is in place over the next five years and will be removed in 2028. No charging support.
Case 3 (Charging support)	Charging support of 1.5 NOK/kWh, which is in place over the whole time period (2023 - 2040). No investment support.
Case 4 (High-support case)	The existing investment support (40% of additional investment) and charging support of 1.5 NOK/kWh. Both are in place over the whole time period (2023 - 2040).



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4

Figure 6.12: Share of the new BETs each year in the four cases for government support described in Table 6.5. The development is shown for the slow, base, and rapid infrastructure scenarios.

The results show that if Norway is to reach the goal that 50% of all new trucks sold are zero-emission in 2030, a combination of support schemes is necessary. The goal is reached in Cases 1, 3, and 4, regardless of the infrastructure scenario. These cases assume that investment support is present over the entire time period. However, in Case 2, when the investment support is removed after five years, the goal is only reached in the rapid scenario for infrastructure development. This means that the government has to make substantial infrastructure investments during the next 5 years to reach the goal.

A comparison of the total discounted costs for the different cases is shown in Table 6.6. This shows what the different cases will cost the government. Case 4 is the most expensive as it is a high-support scenario, and Case 2 is the least costly as it represents less subsidies. The cost of Cases 1 and 3 is more dependent on the infrastructure scenario. In the rapid development scenario, Case 3 is more expensive, whereas, in the base development scenario, Case 1 is more expensive. Despite Case 2 being a low-support scenario, the goal of in NTP of 50% of all new trucks being zero-emission is still reached in the rapid development scenario. Furthermore, the costs associated with the rapid development scenario in Case 2 remains lower than the cost in the base development scenario across the other cases. As a result, this case is the most cost-effective option for accomplishing the goal outlined in NTP.

Figure 6.13 shows how the cost of providing investment support and charging support changes over time in the base scenario. We observe that providing investment support is the most expensive in the beginning, but by 2034, providing charging support is more expensive. This is due to the decreasing investment costs and the increased amount of BETs requiring charging support.

Table 6.6: Comparison of costs for different cases of government support in three infrastructure development scenarios. Costs are discounted back to present value using a social discount rate of 4%, and support cases are described in Table 6.5.

		Infrastructure scenario		
		Slow	Base	Rapid
Support case	**Support type**	*Total discounted costs (BNOK) 2023 - 2040*		
Case 1	Infrastructure	2.6	6.1	10.4
	Charging	0.0	0.0	0.0
	Investment	18.9	21.2	25.9
	Total	**21.5**	**27.3**	**36.3**
Case 2	Infrastructure	2.6	6.1	10.4
	Charging	0.0	0.0	0.0
	Investment	4.7	4.7	5.7
	Total	**7.3**	**10.8**	**16.1**
Case 3	Infrastructure	2.6	6.1	10.4
	Charging	11.4	16.5	36.9
	Investment	0.0	0.0	0.0
	Total	**14.0**	**22.6**	**47.3**
Case 4	Infrastructure	2.6	6.1	10.4
	Charging	13.3	19.2	39.0
	Investment	20.1	23.3	26.6
	Total	**36.0**	**48.6**	**76.0**

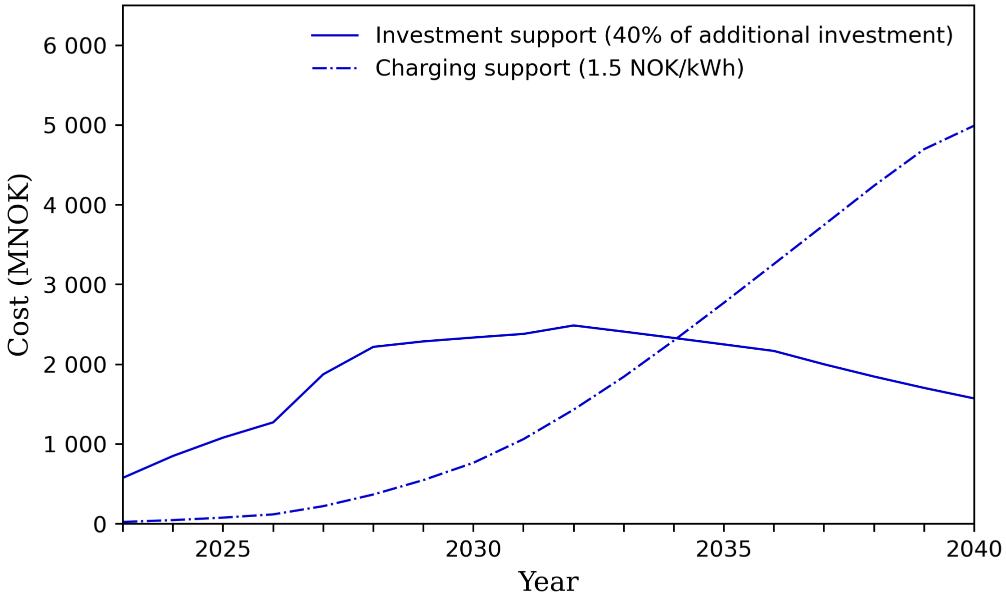


Figure 6.13: Comparison of the annual costs for charging support and investment support in the base scenario for infrastructure development. Assumes Case 4 in Table 6.5.

Chapter 7

Discussion

This chapter interprets the main results and discusses the modeling limitations. Section 7.1 discusses how the TCO varies for the different company specifications and the reason behind that. In Section 7.2, we discuss the variability of the TCOs and the individual cost components that the TCO consists of. In Section 7.3, we consider the effect that the assumptions behind charging infrastructure have on the results. Lastly, in Section 7.4, we discuss the effect that governmental support can have on the investment decision.

7.1 Segmentation

Our findings show that BETs already have a lower TCO than DTs in the short-haul segment. Based on this, a company only operating within this segment should invest in BETs instead of DTs. This segment is not as vulnerable to infrastructure uncertainty, as most of the charging can be done off-shift using home chargers. Refueling inconvenience is close to zero in 2023, and off-shift charging is cheaper than using public charging stations. This is why the short-haul segment is better suited for electrification now than the long-haul. However, the segmentation does not capture the geographical differences in Norway and thus has a limitation. A company based in a small remote town doing short-haul transportation will not obtain the advantage of build-out around main cities, meaning that the refueling inconvenience will be higher. Additionally, the definition of short-haul varies depending on the area. Our segmentation is, therefore, most suitable for companies that are based in cities. However, it is possible to use slow at-home charging also for the charging required during the work shift. This will lead to an increased waiting time for trucking companies, but might still be manageable given the small amount of charging needed.

For companies only doing long-haul transportation, the results show that BETs are not cost-competitive yet. The main reason for this is twofold. First, charging is more expensive in this segment since a higher proportion of the charging is high-speed public charging. Second, as the driving distance increases, the truck relies more on developed charging infrastructure and is thereby penalized heavier when this is not present. The infrastructure scenario is, therefore, a determining factor for the optimal investment timing, and a network of charging infrastructure in various locations is needed for BETs to be cost-competitive in this segment.

Mixed transportation is included as a separate segment because data from NLF shows that it represents the majority of companies. This was, therefore, the base case for our analysis. Furthermore, this is where we see most differences between companies of various sizes. This is caused by the differences in fleet flexibility, as companies need to have a truck suitable for the transport mission in the right location and at the right time. Large companies can more easily benefit from less infrastructure build-out because they can invest in some BETs to use for short-haul and still keep some DTs to use for other assignments. On the other hand, small companies do not have the flexibility of switching between different vehicles. Medium-sized companies lie somewhere in between. They do have the possibility to switch between vehicles, but since they possess fewer vehicles than large companies, the risk of not being able to perform certain assignments and losing flexibility is higher. The results show that the difference in company size could be a major contributing factor when it comes to investment timing for the mixed transport segment. However, the mixed transportation segment builds on some assumptions which are important to keep in mind when interpreting the results. We assume that the companies have a 50/50 split between short- and long-haul, but in reality, the companies could have various ratios of short- and long-haul. Additionally, the mixed transportation segment assumes that the company also owns DTs, and this must hold for the calculations to be correct. Including this in the calculation requires fleet composition models, which is beyond the scope of this thesis. It is, therefore, important that the mixed-haul transport segment does not replace a larger fraction of their fleet than the fraction they do short-haul transportation.

The segmentation into transport distance and company size encompasses all companies regardless of the goods that they transport. Still, the suitability of BETs might differ for companies transporting various goods. A lot of the goods transported in Norway are timber, metals, or sand, which might result in a load too heavy for BETs to be cost-effective. However, data from NLF suggests that the majority of companies transport different types of goods. This means that even though BETs might not be suitable for all loads, it is likely that the company could use the BET for other assignments.

7.2 Cost Structure

There are several cases where the expected TCO for DTs is higher than for BETs but where the distributions start to overlap. This means that the maximum value for the TCO for DTs is higher than the expected value for BETs. Consequently, risk-averse companies might prefer to invest in BETs to obtain a higher but more predictable cost. Furthermore, the results show that the standard deviation for the TCO is increasing for segments with longer driving distances. This is because they have a higher energy consumption which makes these segments more vulnerable to changes in energy prices. This increase is lower for BETs than for DTs because the energy costs for DTs are more vulnerable to variations in the underlying stochastic process. The reason for this is twofold. First, the electricity price data has a smaller sample space than the crude oil price data. Moreover, electric powertrains are more efficient than ICE powertrains. This means that the amount of energy needed to move the truck forward is lower for BETs than for DTs. Companies that want less variation linked to daily operating costs might therefore choose to invest in a BET instead of a DT. Furthermore, as capital costs decrease and refueling inconvenience is reduced, BETs will be the most cost-effective alternative for all company specifications due to their low operational costs.

We considered a charging station surcharge of 6.49 NOK/kWh, based on the estimated surcharge at one existing public charging station for BETs. However, this likely represents an upper limit for the surcharge, as the station can set its own surcharge when they are the only operator. As the number of charging facilities grows, competition between operators may lead to a reduction in surcharges. Additionally, accurately predicting the cost of building public charging stations for trucks is challenging, and the surcharge will most likely be reflected in this cost. The surcharge will vary depending on the location, with more remote areas potentially having a higher surcharge associated with them. It is, therefore, uncertainty tied to this value. However, the results for government charging support can be used to compare different charging station surcharge levels, as it represents a surcharge reduction of 1.5 and 3 NOK/kWh.

The initial investment cost in BETs is about 2-3 times higher than for DTs, and even with the existing investment support, capital costs are much higher. For small companies, access to this capital could be more difficult than for large companies, as the trucking industry is known to have low margins. Larger companies can also spread the costs between multiple vehicles, which provides less risk. This can delay the optimal investment timing for small companies even further. Additionally, we assume that technological improvements in batteries and powertrains for BETs lead to a decrease in capital costs in the coming years. If this progression happens more rapidly or slowly than estimated, it will affect the optimal investment timing.

The residual value for both DTs and BETs is set to 20% all years, but this could be subject to change. Fossil fuels are expected to be phased out and replaced by zero-emission vehicles in the future. The residual value for DTs could therefore drop as society is no longer interested in this technology. This is especially likely if charging infrastructure for BETs is built out so that BET costs are significantly reduced. This could, in turn, lead to the residual value for BETs being higher as they are in higher demand. However, a lot of trucks are resold to other countries after being used in Norway. Since Norway is a leading country in using electric vehicles, the transition to zero-emission road freight might happen here earlier than in other countries. This suggests that DTs can still be sold internationally after their usage, meaning that the residual value will not necessarily drop. Regardless of this, a higher residual value for BETs could still be likely, and more research in this area should be done.

The results from the survey of NLF's members showed that only 30% base their investment decision on TCO analyses or other cost calculations, whereas the rest do not use any decision tools. This could imply that even though the results show that BETs are more cost-effective than DTs in many segments, companies would still not invest. This could either be because they are not aware of the cost advantages of using BETs or because other factors are making them hesitant to invest. If these factors are the lack of infrastructure and the uncertainty associated with BETs, which are not usually addressed and quantified in TCO analyses, then the results in this thesis might make more companies willing to invest.

7.3 Charging Infrastructure

The fact that costs are higher for smaller companies and for companies operating within a longer range comes from the assumption that fewer available stations give a higher StA parameter and, thereby, more refueling inconvenience. These assumptions stem from our literature review, a survey of truck drivers, and conversations with actors in the industry. However, quantifying this difference in a parameter is something that has not been done previously to the same extent. We based the scale for StA on Lajevardi et al. (2022), but the numbers used for various years deviate from their choice as they are adjusted to the Norwegian market. Additionally, we added a new dimension of company size to highlight further differences between companies. This means that the costs for the transportation segments and the company sizes are not exact; it is mainly an attempt to highlight the differences between trucking companies. With that said, the obtained results do represent differences that we expect, and it reflects the research done in conjunction with this thesis.

The results show that the hourly waiting cost for trucking companies is an important cost component. We use answers from the survey to NLF members to determine the waiting cost. However, 45% of the respondents stated that they do not know what the hourly cost of delays for their company is. These answers were disregarded in our model. The fact that almost half of the respondents do not know this cost adds some uncertainty to this estimate, especially since the results show the large effect this cost has on the TCO. It could be that the waiting cost is dependent on the good transported, as some goods are more time-critical than others. This could lead to an even further segmentation of the trucking market. Determining a more certain value for this parameter could therefore be important in order to gain a more precise estimate for the TCO.

A challenge that has not been addressed in the model is the problem of queues at charging stations. If more people invest in BETs than the current level of infrastructure can support, queues may arise. This will lead to the waiting time being longer, which will result in increased refueling inconvenience costs. The queue problem will mainly arise at locations where a lot of truck drivers stop. When building out charging stations, the government or operators must therefore do a careful consideration of relevant placement. An additional concern that requires attention is the need for power grid reinforcements that can handle the high charging demand during peak hours.

7.4 Governmental Support

The results show that providing charging support might not be the best option. As there are currently few public charging stations, providing charging support today will have a limited cost effect for the companies already using BETs. One could argue that more trucking companies would invest in BETs once they know charging support is offered. However, if the support is expected to be removed in a few years, they might be more hesitant. Charging support must therefore be in place for some time for the measure to be effective. Moreover, as the number of BETs in the fleet grows, the cost of providing charging support grows accordingly, and keeping it for a long period of time will be costly for the government. On the other hand, the cost of providing investment support does not grow at the same rate. This is due to the expected decrease in BET costs that results in less governmental support needed. This suggests that keeping the investment support for a longer period of time is more cost-effective for the government than introducing charging support. In particular, keeping investment support is important for smaller companies, as accessing significant investment capital can be challenging.

The government will most likely remove the investment support after a while when the number of BETs in the national truck fleet has grown sufficiently. For that reason, the case where government support is removed after 5 years (Case 2) might be the most realistic. The results also showed that the 50% goal can still be reached in this case if the infrastructure is developed rapidly. This is less costly for the government than a base development of infrastructure in all the other higher support cases. Case 2 in the rapid scenario provides more predictability in costs, both for the government and for the truck owners. The total amount of charging support or investment support provided by the government increases with the number of trucks in the fleet, which can be costly if the number of BETs grows faster than expected. Furthermore, there is uncertainty tied to the refueling inconvenience costs for the trucking company, but this disappears when the infrastructure is sufficient. By investing in enough infrastructure to transfer to a rapid development scenario, the cost uncertainty is therefore removed for both parties. We, therefore, argue that this could be the most cost-efficient measure to facilitate the transition to BETs and reduce uncertainty for truck owners.

Even if the goal that 50% of newly sold trucks are zero-emission in 2030 is reached, it still means that a large part of the fleet consists of DTs. Especially since investing in long-haul BETs is not cost-competitive until 2032 in the base scenario and 2036 in the slow scenario. This means that a lot of companies will keep investing in DTs for many years after 2030. As trucks usually have a lifetime of at least 5 years, replacing the entire fleet will take much longer. This suggests that the NTP goal might not be sufficient to facilitate a full transition to zero-emission road freight. Nevertheless, the target is simpler and more manageable compared to the direct goals of reducing CO_2 emissions.

Chapter 8

Concluding Remarks and Further Research

The objective of this thesis is to provide insight into how the Norwegian heavy-duty road transport sector can transition to zero-emission road freight. This is essential for Norway to fulfill its commitment to reducing GHG emissions in accordance with the Paris Agreement. Moreover, zero-emission road freight is necessary for Norway to reach the goal of half of all new trucks being zero emission by 2030. Our research explores how the decision to invest in a truck varies among individual companies and how it is affected by the speed of infrastructure development. Through this analysis, we aim to give insight into which types of trucking companies are best suited for electrification. Furthermore, we aim to identify the most effective measures that the government can undertake to facilitate the transition to zero-emission road freight. In response, we present a comparative TCO analysis for BETs and DTs over the next decade that shows which year investments in BETs are cost-competitive with DTs for a particular trucking segment. This includes a stochastic model that accounts for uncertainty in energy prices, declining BET costs, and different scenarios for infrastructure development.

Our results show that the TCO for BETs is already lower for companies doing short-haul transportation than for DTs. For the other segments, BETs will become cost-competitive in time, but the timing depends on infrastructure availability, the cost of delayed transport, and governmental support schemes. Declining capital costs for BETs, in addition to the current investment support level, contribute to a significant decrease in initial investment costs. However, this is insufficient to reduce the TCO for BETs to the same level as DTs for long-haul transportation. This is primarily because a lack of public infrastructure imposes a significant cost. We further find that the difference in company size is an important factor in the optimal investment timing for companies in the mixed transport segment. Large companies doing mixed transport have the flexibility to switch between different vehicles depending on the available infrastructure. In contrast, smaller companies doing mixed transport will lose this flexibility if they invest in BETs prematurely. BETs are, therefore, better suited for companies of larger sizes.

Nevertheless, the government can accelerate the transition by partly subsidizing the build-out of public charging infrastructure, providing charging support, or increasing investment support. We find that subsidizing a rapid infrastructure development scenario by 80% and removing investment support after five years is less costly than keeping investment support or charging support over the entire period combined with subsidizing 50% of the infrastructure cost. This will enable Norway to achieve its target of 50% of new truck investments being zero-emission in 2030. Moreover, financing investments in public infrastructure leads to less uncertainty than the other support schemes, both for the truck drivers and the government.

Our model could be expanded by further segmenting the trucking industry to highlight additional company differences. This could, for example, be by segmenting based on goods transported or geographical location in Norway. Another model expansion could be to include residual value as a stochastic process. In this way, one could include the uncertainty related to the residual value for BETs and DTs and how they affect one another. Additionally, the model could benefit from further research on the refueling inconvenience parameters. As the model is highly sensitive to the waiting cost, more research should be done into the exact cost of delays. Furthermore, the refueling time parameter could be simulated using queuing theory combined with the assumed infrastructure scenario. In this way, one could obtain a more accurate value for the time spent at the charging station that also considers possible queues. The domain of the station availability parameter should also be subject to further research for the calculations to be as accurate as possible. As the model assumes that companies doing mixed transportation must have DTs in their fleet until BETs are cost-competitive in the long-haul segment, more research could be done by including fleet composition models in the TCO analysis. This could, for example, be in terms of the number of DTs needed per BET in the fleet. Further research on the area could also include a comparison of BETs with other zero or low-emission technologies such as FCETs or biofuel trucks. In this type of study, it would be interesting to make comparisons of technology performance for different transport distances. More research on the exact costs of infrastructure development is also necessary. Our model use estimates that do not include area costs and power grid reinforcements, which are costs that are likely to occur when infrastructure is built out.

Bibliography

Addae-Dapaah, K. (2012). Appraisal and cost–benefit analysis. In S. J. Smith (Ed.), *International Encyclopedia of Housing and Home* (pp. 70–75). San Diego: Elsevier. doi:`10.1016/B978-0-08-047163-1.00607-X`.

Afshar, S., Macedo, P., Mohamed, F., & Disfani, V. (2021). Mobile charging stations for electric vehicles — a review. *Renewable and Sustainable Energy Reviews*, *152*, 111654. doi:`10.1016/j.rser.2021.111654`.

Ahmad, F., Alam, M. S., Alsaidan, I. S., & Shariff, S. M. (2020). Battery swapping station for electric vehicles: opportunities and challenges. *IET Smart Grid*, *3*, 280–286. doi:`10.1049/iet-stg.2019.0059`.

Al-Hanahi, B., Ahmad, I., Habibi, D., & Masoum, M. A. (2022). Smart charging strategies for heavy electric vehicles. *eTransportation*, *13*, 100182. doi:`10.1016/j.etran.2022.100182`.

Alp, O., Tan, T., & Udenio, M. (2022). Transitioning to sustainable freight transportation by integrating fleet replacement and charging infrastructure decisions. *Omega*, *109*, 102595. doi:`10.1016/j.omega.2022.102595`.

Altinn (2022). Utgående og inngående avgift. (Accessed 31.01.2022). URL: https://www.altinn.no/starte-og-drive/skatt-og-avgift/avgift/utgaende-og-inngaende-avgift/.

Autopass (2023). Takster og rabatter. (Accessed 20.01.2023). URL: https://www.autopass.no/no/kunde/takster-og-rabatter/.

Barbøl, H. K. (2022). Pilotby for utslippsfri tungtransport. (Accessed 14.03.2022). URL: https://www.mtlogistikk.no/godstransport/pilotby-for-utslippsfri-tungtransport/672345.

Behmiri, N. B., & Manzo, J. (2013). Crude oil price forecasting techniques: A comprehensive review of literature. *SSRN Electronic Journal*, . doi:`10.2139/ssrn.2275428`.

Birkelund, H., Arnesen, F., Hole, J., Spilde, D., Jelsness, S., Aulie, F., & Haukeli, I. E. (2021). *Langsiktig kraftmarkedsanalyse 2021–2040: Forsterket klimapolitikk påvirker kraftprisene*. Technical Report 29/2021 Norges vassdrags- og energidirektorat. URL: https://www.nve.no/energi/analyser-og-statistikk/langsiktig-kraftmarkedsanalyse/.

BloombergNEF (2021). Battery pack prices fall to an average of $132/kwh, but rising commodity prices start to bite. (Accessed 30.01.2023). URL: https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.

BloombergNEF (2022). Lithium-ion battery pack prices rise for first time to an average of $151/kwh. (Accessed 30.01.2023). URL: https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/.

Broback, M. (2021). Why the charging infrastructure for heavy electric trucks is set to expand. (Accessed 16.02.2023). URL: https://www.volvotrucks.com/en-en/news-stories/insights/articles/2021/nov/charging-infrastructure-for-electric-trucks.html.

Bye, E. (2023). Børstad Transport valgte elektrisk: - Nå må vi tenke annerledes rundt logistikken. (Accessed 22.02.2023). URL: https://www.tungt.no/article/view/899026/borstad_transport_valgte_elektrisk_na_ma_vi_tenke_annerledes_rundt_logistikken?ref=newsletter&utm_medium=email&utm_source=newsletter&utm_campaign=daily.

Caverzasi, E., & Godin, A. (2014). Post-Keynesian stock-flow-consistent modelling: a survey. *Cambridge Journal of Economics*, *39*, 157–187. doi:`10.1093/cje/beu021`.

Danebergs, J., Espegren, K. A., Fridstrøm, L., Hovi, I. B., Madslien, A., & Rosenberg, E. (2022). *Veikart for utslippsfri veitransport*. Technical Report 1880/2022 TØI. URL: https://www.toi.no/publikasjoner/veikart-mot-utslippsfri-veitransport-article37511-8.html.

DFØ (2022). Oslo kommune stiller krav til nullutslippstransport og biogass ved vare- og tjenesteleveranser (2019). (Accessed 14.03.2022). URL: https://anskaffelser.no/verktoy/eksempler/oslo-kommune-stiller-krav-til-nullutslippstransport-og-biogass-ved-vare-og-tjenesteleveranser-2019.

Drivkraft Norge (2019). Hva påvirker drivstoffprisene? (Accessed 31.01.2022). URL: https://www.drivkraftnorge.no/nyheter/2019/hva-pavirker-drivstoffprisene/.

EIA (2022). Diesel fuel explained. (Accessed 02.02.2023). URL: https://www.eia.gov/energyexplained/diesel-fuel/factors-affecting-diesel-prices.php.

EIA (2023a). Annual Energy Outlook 2023. (Accessed 23.05.2023). URL: https://www.eia.gov/outlooks/aeo/.

EIA (2023b). Assumptions to the Annual Energy Outlook 2023. (Accessed 20.04.2023). URL: eia.gov/outlooks/aeo/assumptions/.

EIA (2023c). Petroleum and other liquids. (Accessed 02.02.2023). URL: https://www.eia.gov/petroleum/gasdiesel/.

Elskling (2023). Å velge strømavtale. (Accessed 05.30.2023). URL: https://www.elskling.no/stromavtaler.

Energimyndigheten (2022). Stor utbyggnad av el- och vätgasstationer för gods efter beslut från Energimyndigheten. (Accessed 30.01.2023). URL: http://www.energimyndigheten.se/nyhetsarkiv/2022/stor-utbyggnad-av-el--och-vatgasstationer-for-gods-efter-beslut-fran-energimyndigheten/.

Engdahl, H. (2021). How a good charging strategy can extend an electric truck's range. (Accessed 27.01.2023). URL: https://www.volvotrucks.com/en-en/news-stories/insights/articles/2021/nov/How-a-good-charging-strategy-can-extend-an-electric-trucks-range.html.

Enova (2021). Tunge elektriske kjøretøy. (Accessed 30.01.2023). URL: https://www.enova.no/bedrift/landtransport/tunge-elektriske-kjoretoy/.

Enova (2022). Bedriftslading for tunge kjøretøy. (Accessed 26.01.2023). URL: https://www.enova.no/bedrift/landtransport/bedriftslading-for-tunge-kjoretoy/.

Figenbaum, E., Ydersbond, M., I, Amundsen, H., A, Pinchasik, R., D, Thorne, J., R, Fridstrøm, L., & Kolbenstvedt (2019). *360 graders analyse av potensialet for nullutslippskjøretøy*. Technical Report 1744/2019 TØI. URL: https://www.toi.no/publikasjoner/360-graders-analyse-av-potensialet-for-nullutslippskjoretoy-article35999-8.html.

Finansdepartmentet (2021). Prinsipper og krav ved utarbeidelse av samfunnsøkonomiske analyser (Rundskriv R-109). (Accessed 01.03.2023). URL: https://www.regjeringen.no/globalassets/upload/fin/vedlegg/okstyring/rundskriv/faste/r_109_2021.pdf.

Fjordkraft (n.d.). Hva er hurtiglading? (Accessed 16.02.2023). URL: https://www.ladestasjoner.no/hurtiglading/hva-er-hurtiglading2/.

Fremtind (2023). Bompengekalkulator. (Accessed 20.03.2023). URL: https://fremtindservice.no/privat/bompengekalkulator/.

Fridstrøm, L., & Østli, V. (2016). *Kjøretøyparkens utvikling og klimagassutslipp. Framskrivinger med modellen BIG*. Technical Report 1518/2016 TØI. URL: https://www.toi.no/publikasjoner/kjoretoyparkens-utvikling-og-klimagassutslipp-framskrivinger-med-modellen-big/-article34059-8.html.

Funk, C. (2018). Forecasting the real price of oil - time-variation and forecast combination. *Energy Economics*, *76*, 288–302. doi:`10.1016/j.eneco.2018.04.016`.

Gjerset, M. (2022). Utslippsfri tungtransport - status kjøretøy og TCO. (Accessed 26.01.2023). URL: https://www.klimaoslo.no/collection/oversikt-over-elektriske-tunge-kjoretoy/.

Glock, C. H., Grosse, E. H., Jaber, M. Y., & Smunt, T. L. (2019). Applications of learning curves in production and operations management: A systematic literature review. *Computers Industrial Engineering*, *131*, 422–441. doi:`10.1016/j.cie.2018.10.030`.

Gnann, T., Funke, S., Jakobsson, N., Plötz, P., Sprei, F., & Bennehag, A. (2018). Fast charging infrastructure for electric vehicles: Today's situation and future needs. *Transportation Research Part D: Transport and Environment*, *62*, 314–329. doi:`10.1016/j.trd.2018.03.004`.

Gollier, C. (2013). *Pricing the planet's future: The economics of discounting in an uncertain world*. Princeton University Press.

Gray, N., O'Shea, R., Wall, D., Smyth, B., Lens, P. N., & Murphy, J. D. (2022). Batteries, fuel cells, or engines? A probabilistic economic and environmental assessment of electricity and electrofuels for heavy goods vehicles. *Advances in Applied Energy*, *8*, 100110. doi:`10.1016/j.adapen.2022.100110`.

Greene, D. L., Ogden, J. M., & Lin, Z. (2020). Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. *eTransportation*, *6*, 100086. doi:`10.1016/j.etran.2020.100086`.

Gunnerød, J., Vagner, D., Korneliussen, R., Wold, K., Bøhnsdalen, E. T., Christiansen, L., Storaker, K., Zafoschnig, L., Hytten, L. M., & Kringstad, A. (2023). *Langsiktig markedsanalyse: Norge, Norden og Europa 2022-2050*. Technical Report Statnett. URL: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/lma/langsiktig-markedsanalyse-2022-2050.pdf.

Hao, X., Lin, Z., Wang, H., Ou, S., & Ouyang, M. (2020). Range cost-effectiveness of plug-in electric vehicle for heterogeneous consumers: An expanded total ownership cost approach. *Applied Energy*, *275*, 115394. doi:`10.1016/j.apenergy.2020.115394`.

Harris, C. M., Shortle, J. F., Thompson, J. M., & grayoss, D. (2008). *Fundamentals of queuing theory*. Wiley series in probability and statistics (4th ed.). Wiley-Blackwell.

Hauge, K. D., Aalhus, J. N., Oseland, S. E., & Wedde, G. (2022). Byene sammen om klimakrav til transport. (Accessed 14.03.2022). URL: https://www.klimaoslo.no/2022/12/19/byene-sammen-om-klimakrav-til-transport/.

Hsieh, I.-Y. L., Pan, M. S., Chiang, Y.-M., & grayeen, W. H. (2019). Learning only buys you so much: Practical limits on battery price reduction. *Applied Energy*, *239*, 218–224. doi:`10.1016/j.apenergy.2019.01.138`.

Interplex (n.d.). Electric vehicle drivetrains only have 20 moving parts compared to over 200 in conventional automobiles. (Accessed on 22.02.2023). URL: https://interplex.com/resources/electric-vehicle-drivetrains-only-have-20-moving-parts-compared-to-over-200-in-conventional-automobiles/.

Johnson, N. (2014). Introduction to EV Powertrain Function and performance - from a battery perspective. (Accessed 22.02.2023). URL: https://autotechdrive.com/electric-vehicle-powertrain/.

Kaminski, V. (2013). *Energy markets*. Risk Books.

Kang, J. E., & Recker, W. W. (2014). Measuring the inconvenience of operating an alternative fuel vehicle. *Transportation Research Part D: Transport and Environment*, *27*, 30–40. doi:`10.1016/j.trd.2013.12.003`.

KlimaOslo (2023a). Oslo kommune gir 25 millioner kroner i støtte til hurtigladere for lastebiler. (Accessed 19.05.2023). URL: https://www.klimaoslo.no/2023/01/06/kommunen-gir-25-millioner-kroner-til-hurtigladere/.

KlimaOslo (2023b). Oslo kommune gir nye 25 millioner kroner i støtte til hurtigladere for lastebiler og busser. (Accessed 19.05.2023). URL: https://www.klimaoslo.no/2023/04/04/oslo-kommune-gir-nye-25-millioner-kroner-i-stotte-til-hurtigladere-for-tunge-kjoretoy/.

Klingenberg, M. (2022). Denne el-lastebilen har bufferstørrelse på batteriet tilsvarende to Teslaer. (Accessed 22.03.2023). URL: https://www.tu.no/artikler/denne-el-lastebilen-har-bufferstorrelse-pa-batteriet-tilsvarende-to-teslaer/516281.

Kople (2023). Ladepris. (Accessed 16.03.2023). URL: https://www.kople.no/veiledning/ladepris.

Koritarov, V. S. (2004). Real-world market representation with agents. *IEEE Power and Energy Magazine*, *2*, 39 – 46. doi:`10.1109/MPAE.2004.1310872`.

Korlyuk, A., Henriksen, G., & Bleskestad, B. (2015). Langt mer enn oljeprisen påvirker bensinprisene. (Accessed 31.01.2022). URL: https://www.ssb.no/energi-og-industri/artikler-og-publikasjoner/langt-mer-enn-oljeprisen-pavirker-bensinprisene.

Krüger, S. H., & Thiis, J. H. (2022). Investments in battery electric trucks: The case of Norway.

Krüger, S. H., & Thiis, J. H. (2023). Truck TCO analysis. (Accessed 06.06.2023). URL: https://github.com/solveighk/Truck-TCO-Analysis.

Lajevardi, S. M., Axsen, J., & Crawford, C. (2022). Simulating competition among heavy-duty zero-emissions vehicles under different infrastructure conditions. *Transportation Research Part D: Transport and Environment*, *106*. doi:`10.1016/j.trd.2022.103254`.

Law Insider (n.d.). Truck body definition. (Accessed on 31.01.2023). URL: https://www.lawinsider.com/dictionary/truck-body.

LeBeau, P. (2022). EV battery costs could spike 22% by 2026 as raw material shortages drag on. (Accessed 03.02.2023). URL: https://www.cnbc.com/2022/05/18/ev-battery-costs-set-to-spike-as-raw-material-shortages-drags-on.html.

Lienert, P., Carey, N., & Shirouzu, N. (2022). Inside China's electric drive for swappable car batteries. (Accessed 26.01.2023). URL: https://www.reuters.com/business/autos-transportation/inside-chinas-electric-drive-swappable-car-batteries-2022-03-24/.

Lin, Z., Ou, S., Elgowainy, A., Reddi, K., Veenstra, M., & Verduzco, L. (2018). A method for determining the optimal delivered hydrogen pressure for fuel cell electric vehicles. *Applied Energy*, *216*, 183–194. doi:`10.1016/j.apenergy.2018.02.041`.

Loftås, B. E. (2022). Det blir både elbilmoms og vektavgift. (Accessed 15.05.2023). URL: https://www.elbil24.no/nyheter/det-blir-bade-elbilmoms-og-vektavgift/77896448.

Lyse (2022). Hva består strømregningen av? (Accessed 01.02.2023). URL: https://www.lyse.no/strom/stromregningen.

Mauler, L., Dahrendorf, L., Duffner, F., Winter, M., & Leker, J. (2022). Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector: A U.S. case study. *Journal of Energy Storage*, *46*, 103891. doi:`10.1016/j.est.2021.103891`.

Mauler, L., Duffner, F., Zeier, W., & Leker, J. (2021). Battery cost forecasting: A review of methods and results with an outlook to 2050. *Energy Environmental Science*, *14*. doi:`10.1039/D1EE01530C`.

Mietzner, D., & Reger, G. (2005). Advantages and disadvantages of scenario approaches for strategic foresight. *International Journal Technology Intelligence and Planning*, *1*, 220–239. URL: https://ssrn.com/abstract=1736110.

Miljødirektoratet (2020). *Klimakur 2030: Tiltak og virkemidler mot 2030*. Technical Report 1625-2020 Miljødirektoratet. URL: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1625/m1625.pdf.

Miller, M., Wang, Q., & Fulton, L. (2017). *Truck choice modeling: Understanding California's transition to zero-emission Vehicle trucks taking into account truck technologies, costs, and fleet decision behavior*. Research Report UC Davis: National Center for Sustainable Transportation. URL: https://escholarship.org/uc/item/1xt3k10x.

NAF (2022). Bompenger for elbil i byene: Sjekk oversikten. (Accessed 15.05.2023). URL: https://nye.naf.no/elbil/bruke-elbil/bompenger-for-elbil.

Nesheim, R. (2021). Posten tar i bruk elektrisk lastebil. (Accessed 22.02.2023). URL: https://elbil.no/posten-tar-i-bruk-elektrisk-lastebil/.

NLF (2019). Får du riktig pris for oppdraget? (Accessed 25.01.2023). URL: https://lastebil.no/Aktuelt/Nyhetsarkiv/2020-og-eldre/2019/Faar-du-riktig-pris-for-oppdraget.

NLF (2022a). Kort- og langsiktige løsninger mot null-utslipp i transportbransjen. Provided by NLF.

NLF (2022b). Kostnadsindeks for lastebiltransport. Provided by NLF.

NLF (2022c). NLFs konjunkturundersøkelse 2021-2022. Provided by NLF.

Noll, B., del Val, S., Schmidt, T. S., & Steffen, B. (2022). Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe. *Applied Energy*, *306*, 118079. doi:`10.1016/j.apenergy.2021.118079`.

NorgesEnergi (2023). Bedrift webspot. (Accessed 15.03.2023). URL: https://norgesenergi.no/bedrift/stromavtaler/webspot/.

NorgesGruppen (2022). ASKO med elektrisk lastebil bygget for langtransport. (Accessed 22.02.2023). URL: https://kommunikasjon.ntb.no/pressemelding/asko-med-elektrisk-lastebil-bygget-for-langtransport?publisherId=89738&releaseId=17950917.

Norsk Elbilforening (2022). Nå er det over 5000 hurtigladere langs norske veier. Det går mot utbyggingsrekord i 2022. (Accessed 16.02.2023). URL: https://kommunikasjon.ntb.no/pressemelding/na-er-det-over-5000-hurtigladere-langs-norske-veier-det-gar-mot-utbyggingsrekord-i-2022?publisherId=15519297&releaseId=17940233.

NTB (2023). Regjeringen: – Ikke aktuelt med nullutslippssoner. (Accessed 02.02.2023). URL: https://www.nettavisen.no/nyheter/regjeringen-ikke-aktuelt-med-nullutslippssoner/s/5-95-875365.

Nykvist, B., & Olsson, O. (2021). The feasibility of heavy battery electric trucks. *Joule*, *5*, 901–913. doi:`10.1016/j.joule.2021.03.007`.

OFV (2023). OFV registreringsstatistikk. (Accessed 19.05.2023). URL: https://ofv.no/registreringsstatistikk.

Oslo Economics (2015). *Konkurranseanalyse av godstransportmarkedet*. Technical Report 2015-9. URL: https://www.regjeringen.no/contentassets/1b0ca25e06434ece9b6420b7198d1746/godstransportmarkedet-2015-9.pdf.

Oslo Kommune (2022). Offentlig tilgjengelig hurtiglading for tunge kjøretøy. (Accessed 26.01.2023). URL: https://klimatilskudd.no/offentlig-hurtiglading-for-tunge-kjoretoy.

O'Leary, M. (2022). Battery packs for heavy-duty electric vehicles. (Accessed 16.02.2023). URL: https://www.volvogroup.com/en/news-and-media/news/2022/may/battery-packs-for-electric-vehicles.html.

Parthanadee, P., Buddhakulsomsiri, J., & Charnsethikul, P. (2012). A study of replacement rules for a parallel fleet replacement problem based on user preference utilization pattern and alternative fuel considerations. *Computers Industrial Engineering*, *63*, 46–57. doi:`10.1016/j.cie.2012.01.011`.

Pau, J. A. L. (2022). Nå kan alle elektriske lastebiler lade på Filipstad. (Accessed 25.01.2023). URL: https://www.klimaoslo.no/2022/10/10/hurtiglading-til-alle-elektriske-lastebiler/.

Peterson, P. P., & Fabozzi, F. J. (2002). *Capital Budgeting: Theory and Practice*. (1st ed.). Wiley Sons.

Phadke, A. A., Khandekar, A., Abhyankar, N., Wooley, D., & Rajagopal, D. (2021). *Why regional and long-haul trucks are primed for electrification now*. Technical Report Lawrence Berkeley National Laboratory.

Prisguiden (2023). Ladestasjon og elbillader. (Accessed 25.04.2023). URL: https://prisguiden.no/kategorier/ladestasjon-og-elbillader.

Regjeringen (2021a). Green Deal – EUs strategi for et klimanøytralt kontinent innen 2050 : Tiltak på transportområdet. (Accessed 03.02.2023). URL:https://www.regjeringen.no/no/tema/transport-og-kommunikasjon/eu-eos-og-internasjonalt-samarbeid-om-transport-og-kommunikasjon/eu-og-eos/eu-og-klima/green-deal--eus-strategi-for-et-klimanoytralt-kontinent-innen-2050/id2694488/.

Regjeringen (2021b). *Nasjonal transportplan 2022–2033*. Technical Report. URL: https://www.regjeringen.no/no/dokumenter/meld.-st.-20-20202021/id2839503/.

Regjeringen (2022a). Avgiftssatser 2022. (Accessed 02.02.2023). URL: https://www.regjeringen.no/no/tema/okonomi-og-budsjett/skatter-og-avgifter/avgiftssatser-2022/id2873933/.

Regjeringen (2022b). Avgiftssatser 2023. (Accessed 30.01.2022). URL: https://www.regjeringen.no/no/tema/okonomi-og-budsjett/skatter-og-avgifter/avgiftssatser-2023/id2929584/.

Reiersen, L. T. (2022). Nå skal også lastebilene til Posten bli elektriske. (Accessed 22.02.2023). URL: https://www.klimaoslo.no/2022/04/05/postens-lastebiler-blir-elektriske//.

Riahi, K., Rubin, E. S., Taylor, M. R., Schrattenholzer, L., & Hounshell, D. (2004). Technological learning for carbon capture and sequestration technologies. *Energy Economics*, *26*, 539–564. doi:`10.1016/j.eneco.2004.04.024`. EMF 19 Alternative technology strategies for climate change policy.

Rustad, M. E. (2021). Regjeringen vil øke CO2 avgiften kraftig. (Accessed 02.02.2023). URL: https://e24.no/det-groenne-skiftet/i/dnkVyJ/regjeringen-vil-oeke-co2-avgiften-kraftig.

Scania (n.d.). Electric trucks. (Accessed 16.02.2023). URL: https://www.scania.com/group/en/home/products-and-services/trucks/battery-electric-truck.html.

Shahidehpour, M., Yamin, H., & Li, Z. (2003). *Market operations in electric power systems: forecasting, scheduling, and risk management*. John Wiley & Sons.

Sintef (2022). Infrastruktur for fylling og lading. (Accessed on 30.01.2023). URL: https://www.sintef.no/fagomrader/utslippsfri-transport/infrastruktur_fylling_og_lading/.

Sirnes, E., Stoltz, G., & Nilsen, H. R. (2021). Nytte-kostnadsanalyse. (Accessed 28.02.2023). URL: https://snl.no/nytte-kostnadsanalyse.

Skatteetaten (2023). Vektårsavgift. (Accessed 30.01.2023). URL: https://www.skatteetaten.no/satser/vektarsavgift/.

Spaun, O.-P. (2022). Kjempesatsing på lastebillading. (Accessed 22.02.2023). URL: https://elbil.no/kjempesatsing-pa-lastebillading/.

SSB (2022a). 07849: Bilparken [Statistics]. (Accessed 19.05.2023). URL: https://www.ssb.no/statbank/table/07849.

SSB (2022b). 08940: Klimagasser, etter kilde (aktivitet), statistikkvariabel, år og komponent [statistics]. (Accessed 08.05.2023). URL: https://www.ssb.no/statbank/table/08940/.

SSB (2022c). 10645: Miljøavgifter, etter type avgift (mill. kr) 1995 - 2021. (Accessed 03.03.2022). URL: https://www.ssb.no/statbank/table/10645/.

SSB (2022d). Energi. (Accessed 03.03.2022). URL: https://www.ssb.no/energi-og-industri/energi.

SSB (2022e). Mer godstransport på norske veier. (Accessed 30.01.2023). URL: https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/godstransport-med-lastebil/artikler/mer-godstransport-pa-norske-veier.

SSB (2023a). Bilparken. (Accessed 29.05.2023). URL: https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/bilparken.

SSB (2023b). Godstransport med lastebil. (Accessed 29.05.2023). URL: https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/godstransport-med-lastebil.

Statens Vegvesen (2021). Hvem kan kjøre i kollektivfelt? (Accessed 30.01.2023). URL: https://www.vegvesen.no/trafikkinformasjon/langs-veien/trafikkregler/kollektivfelt/.

Statens Vegvesen (2023a). Autopass-regulativ for ferjetakster. (Accessed 16.03.2023). URL: https://www.vegvesen.no/globalassets/fag/trafikk/ferje/autopass-regulativ-for-ferjetakster-gjeldende-fra-1-januar-2023.pdf.

Statens Vegvesen (2023b). Oppdatert status på nullutslippskjøretøy. (Accessed 26.01.2023). URL: https://www.vegvesen.no/fag/fokusomrader/baerekraftig-mobilitet/nullutslippsmalene/.

Statens Vegvesen (n.d.). Daglig kjøreperiode og pauser. (Accessed 17.03.2023). URL: https://www.vegvesen.no/kjoretoy/yrkestransport/kjore-og-hviletid/daglig-kjoreperiode/.

Statnett (2022a). Derfor har vi prisområder. (Accessed 02.02.2023). URL: https://www.statnett.no/om-statnett/bli-bedre-kjent-med-statnett/om-strompriser/fakta-om-prisomrader7.

Statnett (2022b). Om strømpriser. (Accessed 01.02.2023). URL: https://www.statnett.no/om-statnett/bli-bedre-kjent-med-statnett/om-strompriser/.

Stevens, S. (2016). What is a powertrain or drivetrain? (Accessed on 31.01.2023). URL: https://www.whichcar.com.au/car-advice/what-is-a-powertrain-or-drivetrain.

Stølen, S. I. (2019). Tjener stort på tvilsomme innenriksoppdrag. (Accessed 27.05.2023). URL: https://lastebil.no/Aktuelt/Nyhetsarkiv/2021-og-eldre/2019/Tjener-stort-paa-tvilsomme-innenriksoppdrag.

Stølen, S. I. (2020). Nå kan du kjøre 24-meters vogntog med totalvekt på 60 tonn i norge. (Accessed on 31.01.2023). URL: https://lastebil.no/Aktuelt/Nyhetsarkiv/2020-og-eldre/2020/Naa-kan-du-kjoere-24-meters-vogntog-med-totalvekt-paa-60-tonn-i-Norge.

Tarroja, B., Zhang, L., Wifvat, V., Shaffer, B., & Samuelsen, S. (2016). Assessing the stationary energy storage equivalency of vehicle-to-grid charging battery electric vehicles. *Energy*, *106*, 673–690. doi:`10.1016/j.energy.2016.03.094`.

Tensio (2023). Nettleie, priser og avtaler. (Accessed 15.03.2023). URL: https://ts.tensio.no/kunde/nettleie-priser-og-avtaler.

Thema Consulting (2022). Grønt landtransportprogram. infrastrukturkostnader for etablering av et nettverk av energistasjoner til tungtransport. (Accessed 19.05.2023). URL: https://www.nho.no/contentassets/141d3fbadf19403a9a156aeb6a0d652a/220128-_infrastruktur-til-tungtransport-sluttrapport-thema.pdf.

United Nations (n.d.). The Paris agreement. (Accessed 17.03.2023). URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

U.S. Department of Energy (2022). How do all-electric cars work? (Accessed 27.01.2023). URL: https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work.

U.S. Department of Energy (n.d.a). How do diesel vehicles work? (Accessed on 31.01.2023). URL: https://afdc.energy.gov/vehicles/how-do-diesel-cars-work.

U.S. Department of Energy (n.d.b). How do fuel cell electric vehicles work using hydrogen? (Accessed 22.03.2023). URL: https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work.

U.S. Department of Energy (n.d.c). Maintenance and safety of electric vehicles. (Accessed 03.02.2023). URL: https://afdc.energy.gov/vehicles/electric_maintenance.html.

U.S. Department of Energy (n.d.d). Vehicle weight classes & categories. (Accessed on 31.01.2023). URL: https://afdc.energy.gov/data/10380.

Vagner, D., Gunnerød, J., Kringstad, A., Korneliussen, R., Christiansen, L., & Hytten, L. M. (2022). *Kortsiktig markedsanalyse 2022-27*. Technical Report Statnett. URL: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/kma2022-2027.pdf.

Vanhaverbeke, L., Schreurs, D., De Clerck, Q., Messagie, M., & Van Mierlo, J. (2017). Total cost of ownership of electric vehicles incorporating vehicle to grid technology. In *2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)* (pp. 1–6). doi:`10.1109/EVER.2017.7935931`.

Viter, I. (2022). Hva koster det å installere elbillader. (Accessed 25.04.2023). URL: https://monta.com/no/blogg/hva-koster-det-a-installere-elbillader/.

Volvo (2022). Volvo's heavy-duty electric truck is put to the test: excels in both range and energy efficiency. (Accessed 22.03.2023). URL: https://www.volvotrucks.com/en-en/news-stories/press-releases/2022/jan/volvos-heavy-duty-electric-truck-is-put-to-the-test-excels-in-both-range-and-energy-efficiency.html.

Vose, D. (2008). *Risk Analysis: A Quantitative Guide*. (3rd ed.). John Wiley & Sons.

Wallbox (n.d.). Ev charging current: What's the difference between ac and dc? (Accessed 08.05.2023). URL: https://wallbox.com/en_catalog/faqs-difference-ac-dc#.

Wang, S., Li, J., Liu, X., Zhao, E., & Eghbalian, N. (2022). Multi-level charging stations for electric vehicles by considering ancillary generating and storage units. *Energy*, *247*, 123401. doi:`10.1016/j.energy.2022.123401`.

Weron, R. (2014). Electricity price forecasting: A review of the state-of-the-art with a look into the future. *International Journal of Forecasting*, *30*, 1030–1081. doi:`10.1016/j.ijforecast.2014.08.008`.

Wikse, K. A. (2022). Bilmotor. (Accessed 22.02.2023). URL: https://snl.no/bilmotor.

Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the aeronautical sciences*, *3*, 122–128. doi:`10.2514/8.155`.

Wu, G., Inderbitzin, A., & Bening, C. (2015). Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments. *Energy Policy*, *80*, 196–214. doi:`10.1016/j.enpol.2015.02.004`.

Xu, M., Meng, Q., & Liu, K. (2017). Network user equilibrium problems for the mixed battery electric vehicles and gasoline vehicles subject to battery swapping stations and road grade constraints. *Transportation Research Part B: Methodological*, *99*, 138–166. doi:`10.1016/j.trb.2017.01.009`.

Yukun, L. (2023). Battery swapping key for heavy-duty trucks. (Accessed 01.03.2023). URL: https://www.chinadaily.com.cn/a/202301/18/WS63c74916a31057c47ebaa452.html.

Zhu, F., Li, L., Li, Y., Li, K., Lu, L., Han, X., Du, J., & Ouyang, M. (2023). Does the battery swapping energy supply mode have better economic potential for electric heavy-duty trucks? *eTransportation*, *15*, 100215. doi:`10.1016/j.etran.2022.100215`.

Ziel, F., & Steinert, R. (2018). Probabilistic mid- and long-term electricity price forecasting. *Renewable and Sustainable Energy Reviews*, *94*, 251–266. doi:`10.1016/j.rser.2018.05.038`.

Appendix

A Survey to Members of NLF

This appendix shows the questions and answers to the survey we sent out to 526 members of the National Trucking Association (NLF) in February 2023. There were 268 respondents, which is a 50% response rate, representing 2526 trucks. The respondents came from trucking companies of various sizes located in different locations in Norway. Most of them transport different types of goods and do a combination of short- and long-haul driving.

1. What is the average annual driving distance for the trucks you operate?

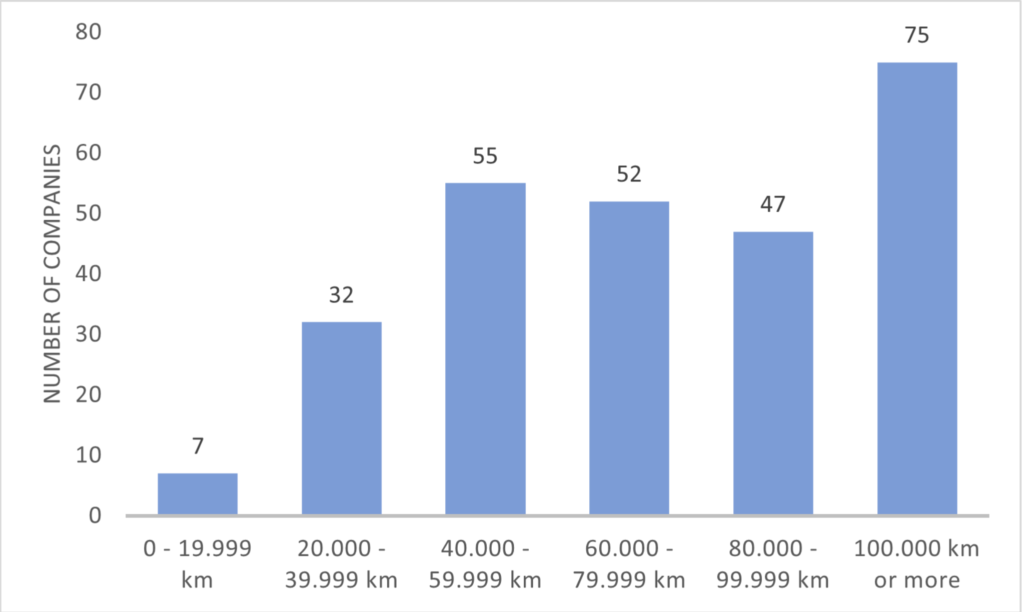


Figure 1: Number of respondents that answered the different intervals for annual driving distance.

2. To which degree are the daily driving routes fixed or variable from day to day? Answer on a scale from 1-5, where 1 indicates only fixed routes and 5 indicates a lot of variation.

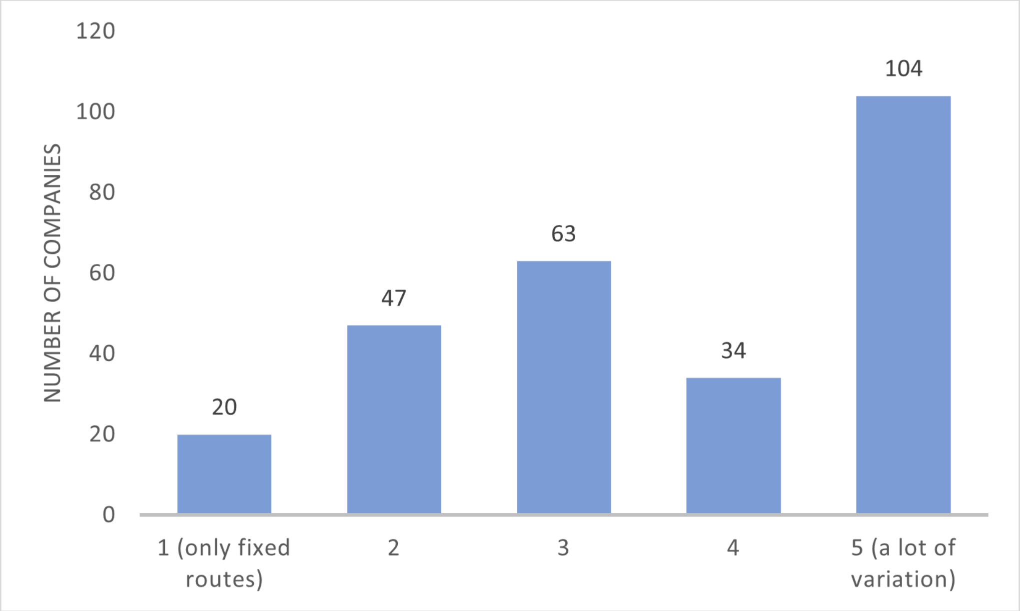


Figure 2: Number of respondents that answered the different options for the variability of routes.

3. How important is flexibility in the usage of the trucks? Flexibility is defined as the ability to drive both long and short lengths and various distances. Answer on a scale from 1-5.

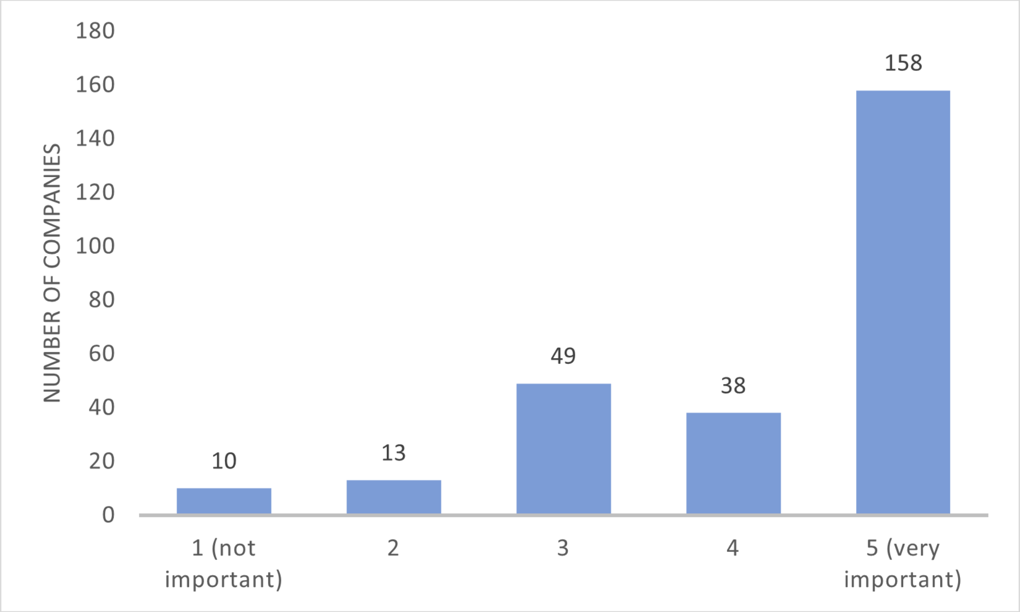


Figure 3: Number of respondents that answered the different options for the importance of flexibility.

4. How many trucks are usually parked in these locations at night?

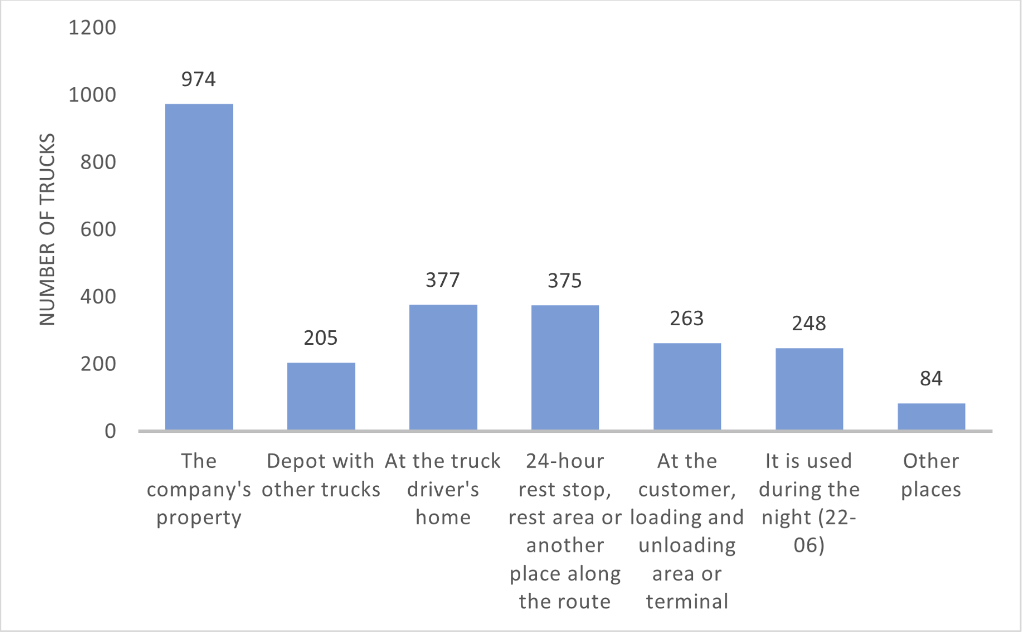


Figure 4: Number of trucks parked in each location at night. The respondents could select multiple locations and register the number of trucks in each one. A total of 2526 trucks were located.

5. What is the estimated hourly cost if the transport is delayed?

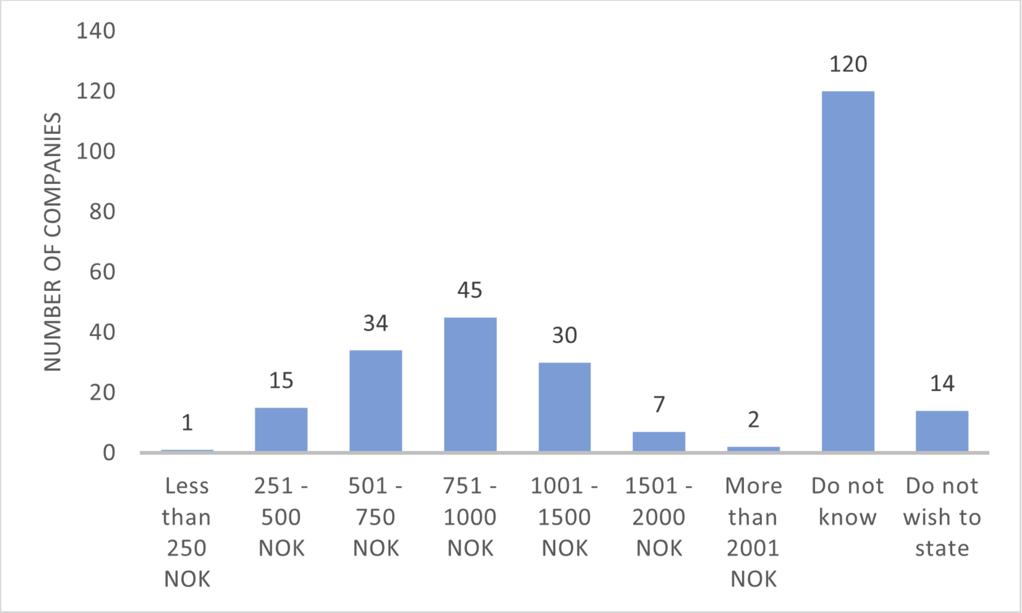


Figure 5: Number of respondents that answered the different cost intervals for the cost of delays.

6. What does the company use as a basis when making investment decisions?

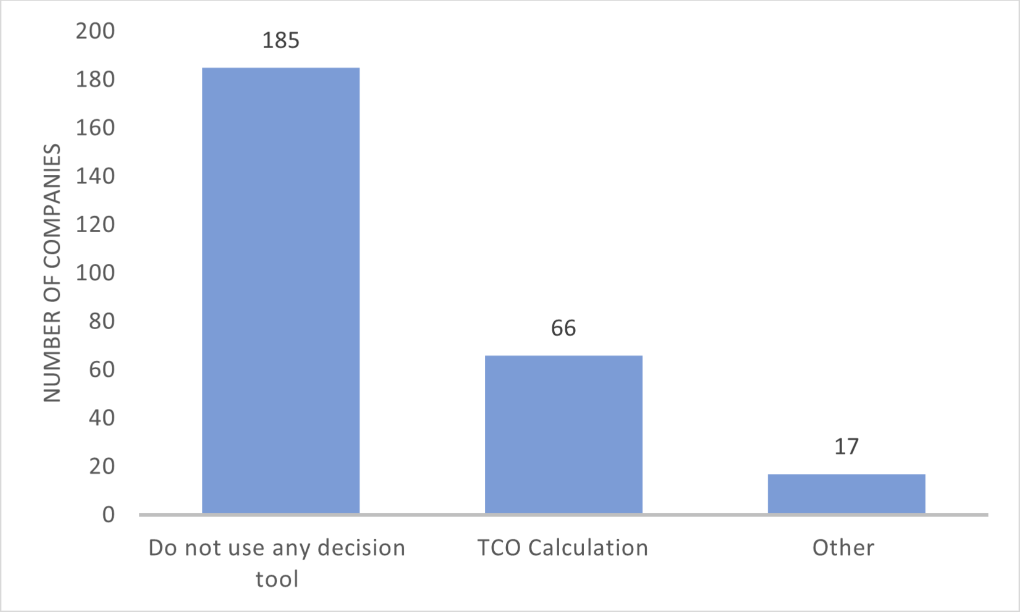


Figure 6: Number of respondents that answered that they use a decision tool when making investment decisions.

7. If the company were to invest in a new truck today, which discount rate would you use?

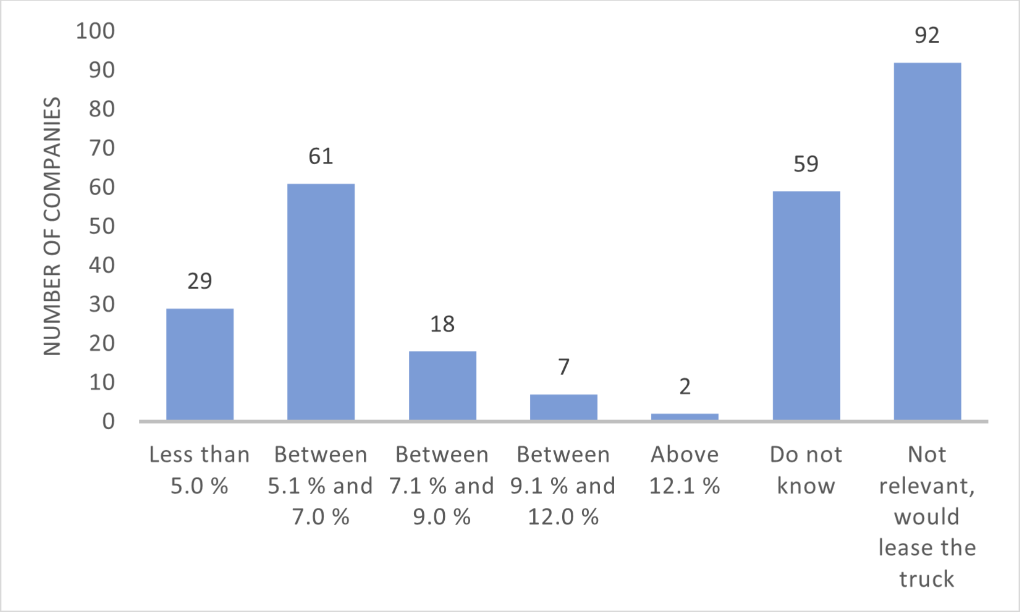


Figure 7: Number of respondents that answered the different options for choice of discount rate.

B Electricity Price Predictions

This appendix displays the short and long-term electricity price predictions in øre/kWh from Statnett for 5 different price zones (NO1-NO5) in Table 1. The data for 2023 - 2027 is from Vagner et al. (2022) and the data for 2030 - 2050 from Gunnerød et al. (2023). The base case for CO_2 prices and fuel prices is used. The highest and lowest simulations are read off a chart and, therefore, not reported accurately.

Table 1: Electricity price predictions from Statnett in øre/kWh. This is used in our model to calculate future charging prices.

		Year									
Prize zone	**Scenario**	2023	2024	2025	2026	2027	…	2030	2035	2040	2050
NO1	Highest simulation	-	-	-	-	-		-	-	-	-
	Base case	118	85	60	46	52		48	53	42	40
	Lowest simulation	-	-	-	-	-		-	-	-	-
NO2	Highest sim.	314	254	190	153	160		121	98	82	78
	Base case	130	94	66	50	54		45	53	42	40
	Lowest sim.	37	25	17	13	16		16	26	19	19
NO3	Highest sim.	210	181	179	134	155		139	97	80	74
	Base case	60	40	45	40	50		43	53	41	38
	Lowest sim.	27	16	11	10	13		13	25	19	18
NO4	Highest sim.	121	83	71	59	108		90	82	69	65
	Base case	53	33	30	25	40		35	48	39	37
	Lowest sim.	16	10	8	7	11		10	23	17	16
NO5	Highest sim.	-	-	-	-	-		-	-	-	-
	Base case	114	83	60	46	55		50	53	42	40
	Lowest sim.	-	-	-	-	-		-	-	-	-

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