Socio-economic feasibility study on the implementation of an Electric Road System between the port of Rotterdam and the port of Antwerp

Master Thesis

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TU Delft

SIEMENS

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by

K.L.M. (Kevin) Duijn

in cooperation with Siemens Mobility B.V. and Delft University of Technology

to obtain the degree of Master of Science in
Civil Engineering wit Track Transport & Planning

at Delft University of Technology
to be defended publicly on Friday December 22Th, 2023

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Preface

This Master thesis research is the final results of my Master's in Transport & Planning at the Faculty of Civil Engineering at Delft University of Technology, which I've been engaged in for the past 9 months. Following my Bachelor's in Civil Engineering at Delft University of Technology, I am delighted that I opted for the Master's program in Transport & Planning as my further education. While the bachelor's program presented challenges, the master's program progressed much more smoothly for me.

During my master's program, I discovered that my interest in the transport sector was greater than I had initially anticipated. Halfway in the second year, I had the opportunity to undertake an internship at Siemens Mobility B.V., which was my first internship within a company. I was very pleased that I could continue at Siemens to conduct my master's thesis in the field of Electric Road Systems.
Beyond the actual thesis work, engaging in meetings at the Ministry of Infrastructure and Water Management, attending the kick-off meeting of the E-CORE project in Berlin, and collaborating with three other thesis students have been incredibly enjoyable experiences. It's fascinating to observe that what you're actively involved in during your studies is also emerging in the professional sphere around you. This aspect makes it particularly engaging to discuss with others and share pictures of the Electric Road System construction in Frankfurt.

I would also like to take this opportunity to thank everyone who has supported me during my studies over the past years—my girlfriend, family, friends, and fellow students. I really enjoyed my years in Delft due to the great talks with everyone.

I would also like to thank Emilio Tuinenburg and Erik Koopman for their guidance from Siemens Mobility B.V. Apart from the weekly progress meetings we had, I really enjoyed being present at the office and interacting with all the other colleagues at Siemens and especially within the digital team. It makes me even prouder to have the opportunity to continue working with you. A year ago, I hadn't imagined transitioning from an internship to graduation and then staying on to work. I am very much looking forward to starting in January.

Furthermore, I would like to thank my committee for the past year. I would like to thank Arjan van Binsbergen for the pleasant collaboration during my internship and subsequently during my thesis research. Secondly, I'd like to express my gratitude to Jan Anne Annema for the collaboration and regular input on drafting my SCBA. I would also like to thank Mahnam Saeednia. Although we didn't speak much about my research during my thesis, your feedback was very valuable for me. And finally, Lori Tavasszy, who provided helpful feedback and took us to the Ministry of Infrastructure and Water Management and the E-CORE kick-off meeting in Berlin, making the thesis journey much more enjoyable and unforgettable. I will not forget on the Chinese food we had back then.

K.L.M. (Kevin) Duijn
Zoetermeer, 2023

Executive summary

Reaching the climate goal agreements in the coming years, the total CO_2 emissions should reduce significantly. One way to reach these goals is the decarbonization of the heavy duty trucks. Heavy duty trucks contribute for 28% of the total CO_2 emissions by vehicles, despite its share of fleet of 2% (Transport & Environment 2022). Multiple solutions (regarding fuel types and electrification) are considered for the decarbonization within the heavy duty truck sector. Electrification of heavy duty trucks can be performed by implementing big batteries. The disadvantage of implementing big batteries is that the gross vehicle weight of the heavy duty truck increases significantly when adding a big battery. In addition, trucks do have to charge its battery at a charging station. This can partially be done overnight, but heavy duty trucks transporting long distances should charge their battery during the day as well. (Mareev, Becker, and Sauer 2018; Nykvist and Olsson 2021).
The alternative is the equipment of a smaller battery in combination with an Electric Road System (ERS) construction on the highway. The smaller battery within the heavy duty trucks result in a lower gross vehicle weight of the truck, resulting in an increase in payload (Mareev, Becker, and Sauer 2018). Besides the smaller battery, the trucks do not have to charge at a charging station anymore. The ERS network makes dynamic charging possible for the trucks connected to the ERS network. While connected, the electricity is used directly for driving and for charging the battery. When disconnected from the ERS network, the truck is able to drive using its equipped battery.
Electric Road Systems can be applied via a conductive or inductive connection. Besides conductive and inductive, the heavy duty truck can be charged in three ways, namely: from underneath, from the side or from overhead. From studies and pilots over the last years, the Overhead Catenary Line (OCL) (conductive solution) is seen as the most mature ERS solution (Ainalis, Thorne, and Cebon 2020; Drevland Jakobsen, Are Suul, and Rise 2018, Ramshankar et al. 2023).

To reach the climate goals, European cooperation is needed within the decarbonization of heavy duty trucks. In case of an Overhead Catenary Line (OCL) network, it is most profitable if trucks can travel from country to country while connected to the ERS network. The construction of an entire network cannot be implemented at once, therefore it is important to start with point-to-point connection between two freight handling points, which can guarantee a high utilization at starting phase (Hacker et al. 2023).
Previous studies have been performed to gain insight about the implementation of an ERS infrastructure. In studies as Deshpande et al (2023), Chang et al (2020), Taljegard et al (2019), de Saxe et al (2023), entire ERS infrastructure networks have been studied. Besides the inclusion of an entire network, studies from van Ommeren et al (2022) and de Saxe et al (2022) also take shorter routes into account. The methods used are cost-effective analysis or demonstrator projects (based on pilot studies). The socio-economic feasibility of ERS infrastructure, between two freight handling points, is not addressed yet in literature. As Hacker et al (2023) stated, to succeed with an European ERS network, it is important to start with a point-to-point connection between two freight handling points. The following research question is derived from the research gap found in the literature:

What is the socio-economic feasibility of the implementation of an Electric Road System (ERS), the overhead catenary line system, between two freight handling points?

The case study studied in this research are the three route alternatives between the port of Rotterdam and the port of Antwerp, as shown in figure 1. To test the socio-economic feasibility, a Social Cost Benefit Analysis (SCBA) was performed (Romijn and Renes n.d.). The results for all three route alternatives have been calculated within the SCBA, this creates an overview of all options between the two ports. The time span taken into account in the research is 30 years (2025 - 2054).

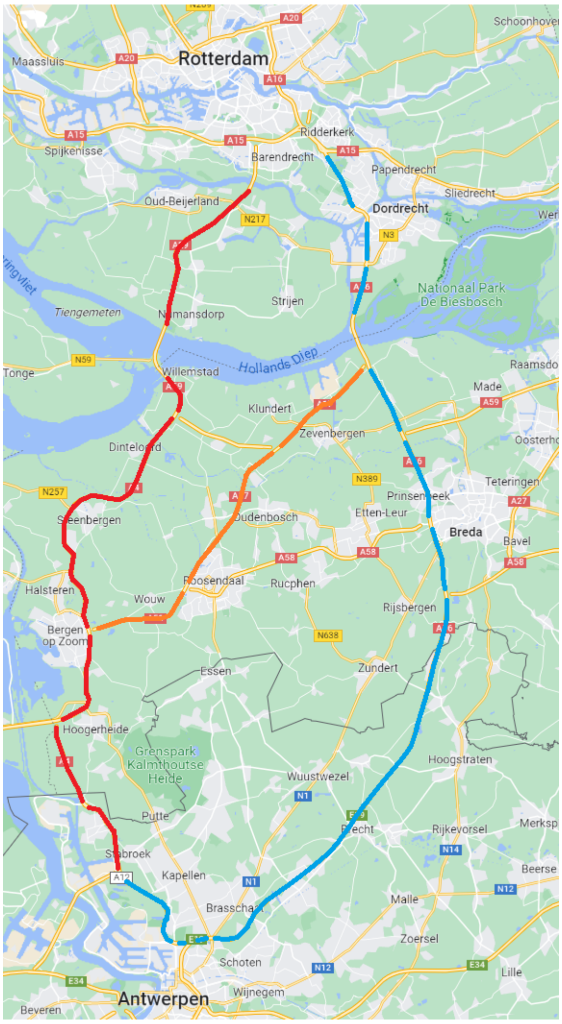

Figure 1: Research area port of Rotterdam - port of Antwerp (Google Maps n.d.)

Within the SCBA, a zero alternative is set up. In this zero alternative the expected future scenario is described, without interventions or policy measures taken. In the zero alternative, the uptake of battery trucks (as electric trucks) is taken into account. This results in a distribution between diesel trucks and battery trucks. For the uptake within the zero alternative, the uptake forecast of Fabius et al. (2020) is used. The battery trucks need charging stations to charge the batteries, in the zero alternative the number of charging stations depends on the number of battery trucks. This means that the increase in charging stations goes alongside the increase of battery trucks.

In addition, opportunity charging is tested in the SCBA. Opportunity charging means that the trucks are able to charge its battery completely at least once a day. This influences the electric truck uptake.

Besides the zero alternative, a zero+ alternative is studied. The difference between the zero+ alternative and the zero alternative is that the construction of the charging stations is finished in 2030. This means that the total number of charging stations needed at the end of the research period (2054) are constructed in 2030.

The policy measure that has been studied is the Electric Road System solution: Overhead Catenary Line system. This alternative is called the policy scenario. In the policy scenario the ERS infrastructure construction is finished in 2030. Before 2030 the uptake of electric trucks consists of battery trucks, followed up with an uptake of catenary trucks alongside diesel trucks and battery trucks. Due to the presence of battery trucks already, charging stations are included in the policy scenario as well.

Due to the policy measure (the implementation of an ERS infrastructure), societal effects will arise. These societal effects can be divided into two types, namely the direct effects and the indirect effects. Direct effects are the effects that result directly from the policy measure taken. The direct effects that occur are monetized if possible. The monetized direct effects are included in the SCBA calculations. The non-monetized direct effects are included in the conclusion. Indirect effects are effects that arise in different markets due to the policy measure. Besides direct and indirect effects, input parameters are needed to fulfill the calculations within the SCBA. These input parameters are: route distance, route ERS distance, mean number of trucks, yearly increase number of trucks, number of trips per day and the number of trips per year. These input parameters are essential in the calculation of the Net Present Values (NPV) and Benefit-Cost (B-C) ratios in the SCBA.
Only costs and benefits are accounted for when a difference arises between the zero(+) alternative and the policy scenario. In cases where costs or benefits occur in varying years, a discount rate of 2.25% is applied. This rate aligns with the Ministry of Finance guidelines (Rijksoverheid 2020). The combination of monetized direct effects and input parameters (variables) are used in the calculations of the SCBA

In table 1, the final results for the SCBA can be seen, the results are expressed in the Net Present Value and the Benefit-Cost ratio. The positive value for the CO_2 cost delta represents a benefit towards transport companies. The CO_2 cost delta shows the difference between the CO_2 emission cost in the policy scenario compared to the zero(+) alternative. It includes all trucks over the time period of 30 years.

Table 1: Final results of the Social Cost Benefit Analysis

Result	Policy scenario compared with zero alternative	Policy scenario compared with zero alternative (opportunity charging)	Policy scenario compared with zero+ alternative
Western route			
CO_2 cost delta (mln. euro)	530	115	95
Net Present Value (mln. euro)	1,080	166	151
Benefit-Cost ratio	3.9	1.5	1.6
Middle route			
CO_2 cost delta (mln. euro)	653	142	118
Net Present Value (mln. euro)	1,358	242	219
Benefit-Cost ratio	4.5	1.7	1.8
Eastern route			
CO_2 cost delta (mln. euro)	1,099	238	199
Net Present Value (mln. euro)	2,355	485	445
Benefit-Cost ratio	5.6	2.0	2.3

From the results, it can be concluded that the implementation of an ERS infrastructure on all three routes is welfare enhancing and thus socio-economic feasible. The NPV results are all positive and the B-C ratios are all higher than 1. The results also show that the NPV results are the highest for the Eastern route (compared to the Middle route and Western route). The higher outcome is mainly caused by two route characteristics: the longer distance of the route and the mean number of trucks. Catenary trucks consume less energy and are less polluting compared to diesel trucks and battery trucks. A longer distance means more energy consumption needed, resulting in bigger differences between the policy scenario and the zero(+) alternative. The lower energy consumption and pollution differences between the truck types is also resulting in a bigger difference in NPV in case of a higher mean number of trucks. The CO_2 emissions cost show a big delta within the results, this means that the CO_2 costs for the total number of trucks is of big influence towards the NPV results.

After the calculations of the SCBA, the direct effects and input parameters have been tested by use of a sensitivity analysis. The sensitivity analysis is performed by adjusting each variable individually. The variables in which the NPV results changed more than 25% (positive or negative) have been tested in more depth by adjusting the variable in more steps. In figure 2, the sensitivity analysis can be seen for the variable: Energy consumption battery trucks. It can be seen that the change in energy consumption of battery trucks result in a linear relation with the NPV results. It can be concluded that small changes in the energy consumption result in big changes in the NPV results. All variables result in a linear relation towards the NPV results.

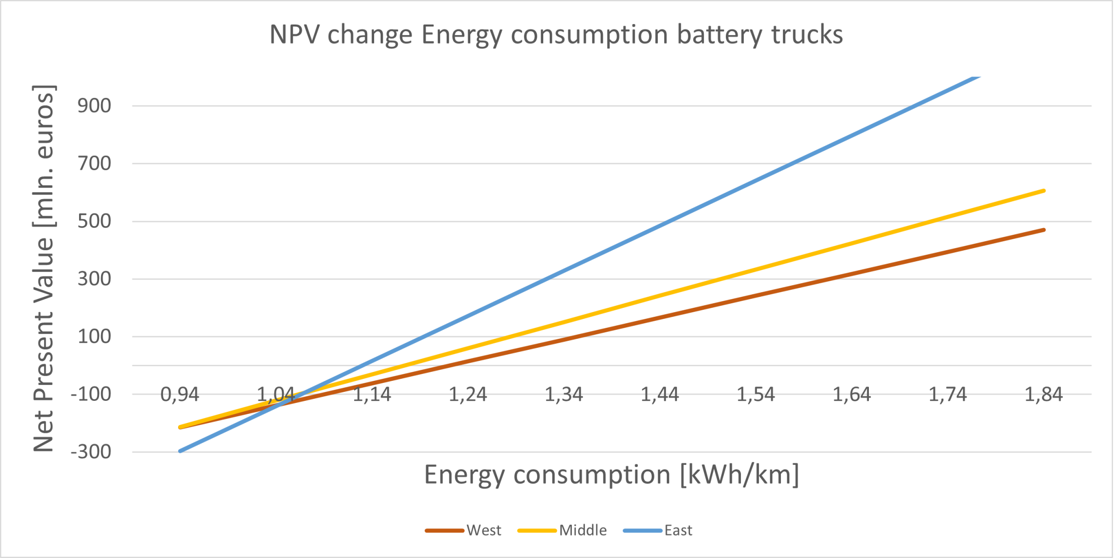

Figure 2: NPV results when adjustments made on the variable: Energy consumption battery trucks

Besides the sensitivity analysis in more depth per variable, the most influencing variables have been tested in combination. In figure 3 the results can be seen for the combination of adjusted variables for the Western route (policy scenario - zero alternative with opportunity charging). The Western route is highlighted in the summary since adjustments in the variables change the NPV results the most.

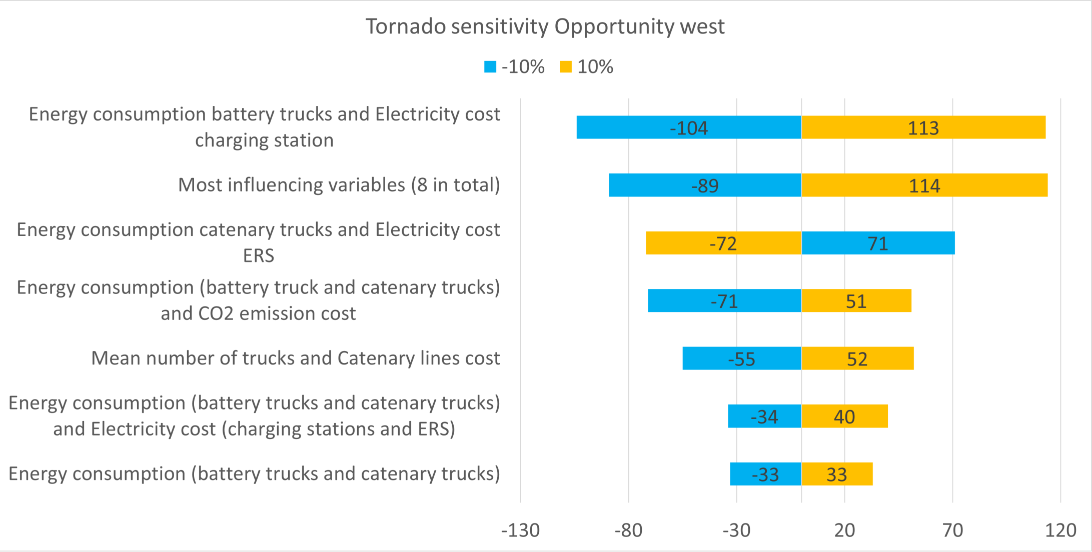

Figure 3: Sensitivity analysis performed on the Western route within the comparison between the policy scenario and zero alternative (including opportunity charging)

Within the SCBA calculations, a couple of limitations emerged in this study. Firstly, the sensitivity analysis showed that multiple variables (direct effects and input parameters) affect the NPV result significantly. This means that small changes in these variables (see figure 3) give different NPV results. All NPV results do have a positive outcome, if the changed NPV is -72% (in figure 3 the combination of Energy consumption catenary trucks and Electricity cost ERS) the NPV is still positive. For the Western route the NPV only becomes negative if the variables Energy consumption battery trucks and Electricity cost charging station are decreased by -10%, the NPV is then changed by -104%, which makes the NPV negative and not welfare enhancing. On the Middle routes and the Eastern route the NPV is under no circumstances changed by more than -100%, so all NPV results are positive.

The values for direct effects and input parameters within future years are uncertain. Therefore, in this research the values are assumed to be fixed values (except for the number of trucks and the battery prices). The sensitivity analysis show that different values for the variables result in different NPV results, this would also be the fact if the value changes over the time span in the study.

In this study all trucks are taken into account that transport between the port of Rotterdam and the port of Antwerp. For the implementation of an ERS infrastructure it would be more interesting to take into account the truck who transport from the port to the other port ('Shuttle' trucks). These are the trucks where the ERS infrastructure is built for, since trucks which go further into Europe should still need a big battery (if the ERS infrastructure is only implemented on this route). These number of trucks are now included with a linear uptake over the years, but this can be supported by subsidies for a faster increase (as mentioned in Dennis Tol et al. 2022).

Besides the number of trucks, the fuel types can be extended on to create a more complete overview. In this study only diesel trucks, battery trucks and catenary trucks are included. Other fuel types are already entering the market. This research therefore can be optimized by adding the other fuel types in the calculations of the SCBA.

To conclude, the NPV results on all three routes show a positive value. This means that the implementation of an ERS infrastructure on all three routes is welfare enhancing and socio-economic feasible under the circumstances in this research. The variables included in the calculations of the SCBA are sensitive towards adjustments. Within this research, these sensitive direct effects and input parameters are chosen to have a fixed value over the time span of the research. In future research it is recommended to vary within the direct effects and input variables over time to investigate the effect on the NPV results. Especially the variables: Energy consumption battery trucks and catenary trucks, Electricity cost charging station and ERS and CO_2 emission cost should be tested more in depth.

From the results, the Eastern route shows the biggest NPV results and the highest B-C ratios for all comparisons. To decide which route is the best it is recommended to perform another decision making method. With the SCBA calculations in this research the most promising route is shown according the monetized effects. In order to make a final decision, the non-monetized effects should be included in the discussion as well. The location of distribution centers can be an important non-monetized variable. Truck companies may be interested in catenary trucks only if their distribution centers are located close to the ERS infrastructure.

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List of Abbreviations

AC-DC - Alternating Current - Direct Current
B-C ratio - Benefit-Cost ratio
BEV - Battery Electric Vehicle
BT - Battery Truck
CBA - Cost Benefit Analysis
CI - Cash Inflow
CT - Catenary Truck
CO - Cash Outflow
CO_2 - Carbon dioxide
CPI - Customer Price Index
DT - Diesel Truck
E - Electricity
E_c - Electricity consumption
E_i - Electricity input
EIA - Environmental Impact Assessment
ERS - Electric Road System
E_s - Electricity storage
E_t - Electricity per truck
g - gram
H_2 - Hydrogen
HDT - Heavy Duty Truck
HGV - Heavy Goods Vehicle
ICE - Internal Combustion Engine
kg - kilogram
km - kilometer
kW - kilowatt
kWh - kilowatt hour
LDT - Light Duty Truck
m - meter
MCA - Multi-Criteria Analysis
MCS - Meggawatt Charging Station
MDT - Medium Duty Truck
mln. - million
MVA - Mega Volt Ampère
n = number of periods
n.d. - no date
NO_x - Nitrogen Oxides
NPV - Net Present Value
OCL - Overhead Catenary Line
PM_v - particulate matter
r = Discount rate
SC - Static Charging
SCBA - Social Cost Benefit Analysis
t - time
TA - Technology Assessment
v - speed
WTW - Well-To-Wheel
ZE - Zero Emission

1
Introduction

1.1. Problem statement

The Paris Climate Agreement was introduced at the Climate Conference in Paris in 2015 as a global effort to reduce greenhouse gas emissions, with the aim of limiting the increase in global temperature to no more than 2 degrees Celsius compared to pre-industrial levels, and an even more ambitious target of limiting the increase to 1.5 degrees Celsius (Zhang, Fujimori, and Hanaoka 2018).

In order to achieve these goals, the European Union has committed to reducing its greenhouse gas emissions by 55% by 2030 and becoming carbon neutral by 2050, while the Netherlands has set a target of reducing emissions by 60% and achieving carbon neutrality by 2050 (European Comission 2021; Plötz, Gnann, et al. 2019; Plötz, Wachsmuth, et al. 2023).

On February 18Th, 2019, the European Union decided to reduce greenhouse gas emissions partly through reducing CO_2 emissions from heavy-duty trucks. This will involve reducing the mean emissions of these trucks by 15% in 2025 and by 30% in 2030 compared to 2019 levels (Volvo Trucks 2019). Despite only accounting for 2% of the total fleet, trucks and buses are responsible for 28% of total CO_2 emissions in Europe, as shown in Figure 1.1. Compared to cars, the relative high carbon emissions of heavy duty trucks makes it evident that focusing on its reduction is an effective way to reduce total carbon emissions. In 2020, the CO_2 emissions from heavy-duty trucks were 28% higher than they were in 1990 (Transport & Environment 2022).

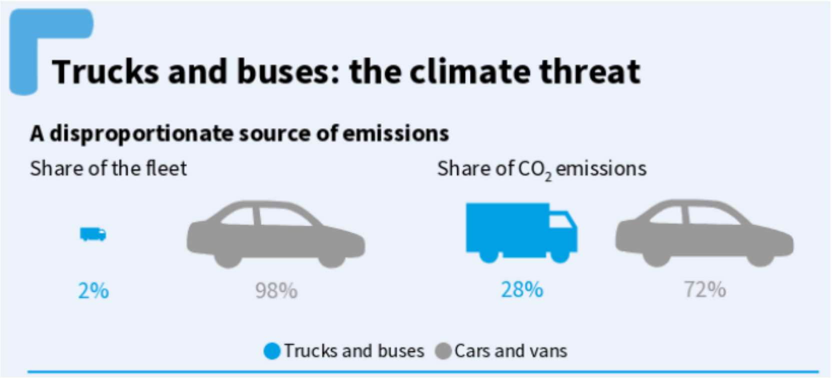

Figure 1.1: Trucks and buses percentage fleet and CO_2 emissions (Transport & Environment 2022)

Therefore, to achieve the environmental goal as agreed upon in the Paris Climate Agreement, the heavy duty truck sector has to be development and shift towards other fuel possibilities. One way of decarbonization, which is already happening with battery trucks, is the electrification of the heavy duty truck sector. Besides the static charging solution of battery trucks, Electric Road Systems (ERS) is considered as solution for the decarbonization of heavy duty trucks. This technology makes dynamic charging possible for electric vehicles.
Scherrer et al (2023) conducted a research of newspaper articles on the different technologies and found the following. As can be seen in figure 1.2, from the different solution alternatives: battery trucks (BEV) are mostly mentioned in newspapers between 2018-2020. The ERS technology is hardly mentioned, as this technology was mostly unknown among its potential users. In the last years researches (Ainalis, Thorne, and Cebon 2020; Deshpande et al. 2023; Mareev and Sauer 2018; De Saxe et al. 2022; Saxe et al. 2023; Scherrer 2023 ; Stütz et al. 2017) have been performed towards ERS and led to it becoming a greater point of discussion nowadays.

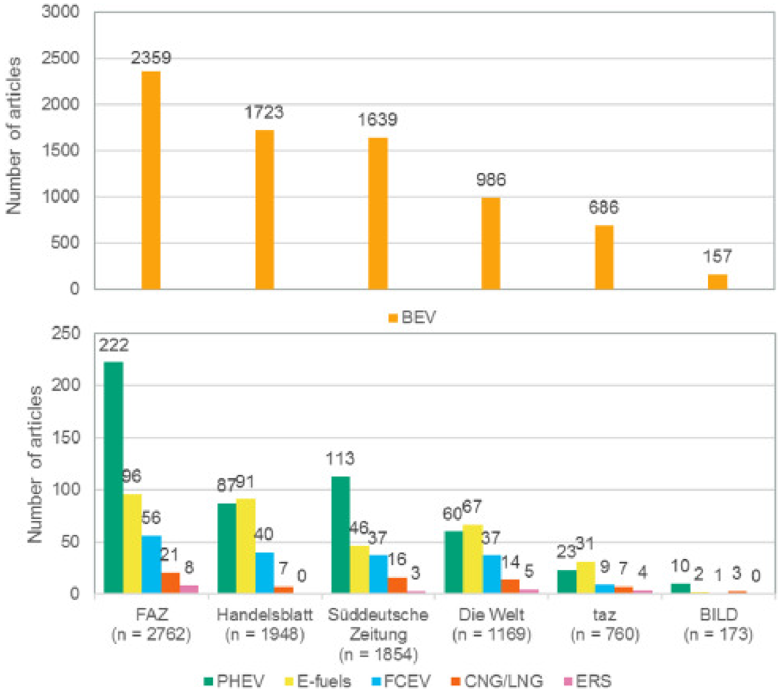

Figure 1.2: Energy technologies mentioned in newspaper from 2018-2020 (graphs have a different scale) (Scherrer 2023)

Dynamic charging via ERS can be executed in a conductive or inductive charging system and in three different ways relative to the construction side (from overhead, from the side, from underneath). The different ERS option can be seen in figure 1.3, it can be seen that the overhead charging option is only possible for the heavy duty truck sector, whilst the other could also be possible for passenger cars.
Besides the contribution to reach the decarbonization goals, implementation of an overhead ERS system can solve other problems. Due to an ERS infrastructure, the battery needed for the trucks travelling underneath it can be decreased significantly. While driving connected to the network, the truck does not have to use its battery (uses the electric directly). Next to the direct use, the truck is able to charge its battery while driving, this results in time savings for the truck drivers, they will not have to charge the battery or refuel at the gas station.

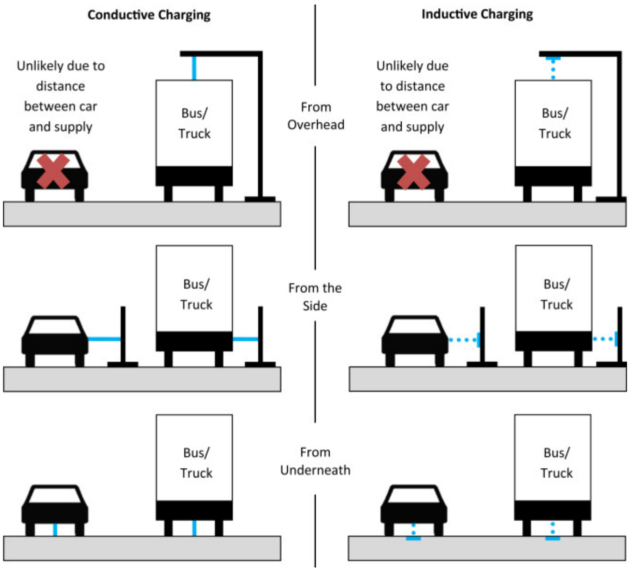

Figure 1.3: Different possible electric road systems (Connolly 2017)

The readiness level for the conductive overhead ERS is higher compared to the inductive overhead ERS technology and the technologies from the side and from underneath, it is seen as the most mature technology at the moment (Ainalis, Thorne, and Cebon 2020; Drevland Jakobsen, Are Suul, and Rise 2018, Ramshankar et al. 2023; Jöhrens et al. 2022).

Previous studies have been performed to gain insight about the implementation of an ERS infrastructure. In studies as Deshpande et al (2023), Chang et al (2020), Taljegard et al (2019), de Saxe et al (2023), the focus of the ERS infrastructure implementation is towards an entire network. The construction of an entire network cannot be implemented at once, therefore it is important to start with point-to-point connection between two freight handling points, which can guarantee a high utilization at starting phase (Hacker et al. 2023). The focus of this study is to test the socio economic feasibility of the conductive overhead ERS on a route between two freight handling points.

1.2. Research objectives

The research objective of this research is to gain more insight in the socio-economic feasibility of the implementation of an ERS infrastructure, between two freight handling points. As a result of the implementation of an ERS infrastructure, different effects arise. Previous studies mostly include the ERS infrastructure as one combined cost parameters. In fact, the ERS infrastructure consists of multiple components which have a different lifetime. Therefore, these different lifetime components are taken into account separately in the calculations of the socio-economic feasibility.

The two freight handling points chosen in this research are the port of Rotterdam and the port of Antwerp. Between these two ports, containers are exchanged on a daily basis, this case study could count as a good starting point for the implementation of a bigger network throughout Europe.

1.3. Research questions

To answer the research objectives stated above, the following main research question is formulated:

What is the socio-economic feasibility of the implementation of an Electric Road System (ERS), the overhead catenary line system, between two freight handling points?

The main research question is answered with the use of the following sub-questions:

1. What are the highway characteristics and limitations that have to be taken into account for the implementation of an ERS infrastructure?
2. Which social effects arise by the implementation of an ERS infrastructure?
3. What other input parameters, besides the social effects, are needed to calculate the feasibility of an ERS infrastructure?
4. What is the Net Present Value according the policy scenario?
5. Which uncertainties, within the direct effects and the input parameters, will lead to big changes in the Net-Present Value calculation?

1.4. Methodology

1.4.1. Methodology alternatives

The most common method for the investigation of new technologies is the Technology Assessment (TA). Within the TA, the conditions and consequences of the new technology is researched and the social effects are expressed (Rip 2001). It takes into account future developments of the technology and helps within the decision making for new infrastructure projects. Three different TA methods are most commonly used within infrastructure projects: the Cost Benefit Analysis (CBA), the Multi-Criteria Analysis (MCA) and the Environment Impact Assessment (EIA) (Niek Mouter 2021).

CBA is a method in which all social costs and benefits of a project are included over the time span of the research. These social costs and benefits are monetized, which makes it possible to compare the effects in the research. All other effects that cannot be monetized are mentioned and included in the final conclusion. In a CBA, the policy measures and effects of the policy measures are included in the policy scenario. This policy scenario is compared to a zero alternative. Within the zero alternative the expected future scenario is not influenced by policy measures. The feasibility of the project is expressed in the difference between the policy scenario and the zero alternative, the Net Present Value (NPV).

MCA is a decision making method to compare different alternatives against multiple criteria (Aruldoss, Lakshmi, and Prasanna Venkatesan 2013). Each of the possible alternatives is evaluated against the criteria involved, which result in scores for all alternatives. Each criteria has its own weight, to visualize its importance. The combination of the scores and weights result in a ranking between the different alternatives. Based on the selected criteria, the result show a presentation of the alternatives taken into account, from best performing to worst performing.

EIA is a method used to assess the significant effects of a proposed project, development or policy measures on the environment before implementation (Morgan 2012). It is an examination of the positive and negative effects that may result from the proposed project, development or policy measures. The main goal is to inform all involved stakeholders with the environmental impacts arising from the project. The result of an EIA are expressed in the predicted environmental impacts and the proposed measures.

1.4.2. Methodology study

SCBA is chosen as the main method for this research. Within this research it is clear which alternative is to be chosen, namely the policy scenario in which an ERS infrastructure is implemented. The outcome of an MCA is a ranked order for different alternatives. In this research the only alternative to be researched is the implementation of the ERS infrastructure. Comparing it to the EIA, besides environmental effects, other effects have to be included as well. The list of effects will be bigger than only the environmental ones.

Moreover, the ERS infrastructure is going to be used in the coming years. Therefore, it is interesting to come with a clear representation of the costs and benefits over the coming years. Within an MCA a time span is not included, the final result is showing an overview for different alternatives against the chosen criteria. The EIA works the other way around. A project is created according the different environmental impacts and comparing alternative project solutions. The result show multiple solution alternatives with a plan for the execution of the projects.
In chapter 2 the theory on the SCBA is described in more detail in combination with the steps included in this research. The methodology contains the route selection within the case study, the zero alternative/policy scenario descriptions, and the SCBA calculations, followed up by the results expressed in the Net Present Value (NPV) and Benefit-Cost ratios.

1.5. Case study research

As described before, the start of an ERS infrastructure network can not be implemented at once, but should start on small scale between two freight handling locations (Andersson et al. n.d.). In this study the two freight handling locations are the port of Rotterdam and the port of Antwerp. Between these two ports, three different route options are possible, as can be seen in figure 1.4. The SCBA in this research contains all three routes. The three route contain a different daily number of trucks, different lengths and different surroundings. In combination with the limitations on highways, for the implementation of the ERS infrastructure, the route segments are selected on which the implementation of the ERS infrastructure is possible. The route segment selection is elaborated in chapter 3.

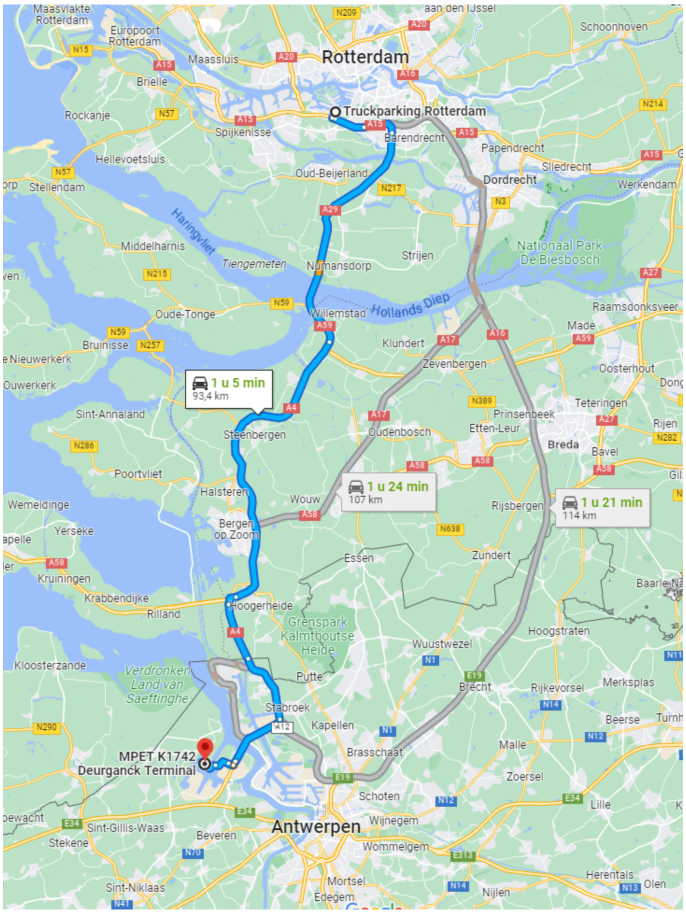

Figure 1.4: Research area port of Rotterdam - port of Antwerp (Google Maps n.d.)

1.6. Structure report

The structure of the report is as follows. In chapter 2 the methodology is explained according the different steps to take within the SCBA. It includes the literature review executed towards the steps of the SCBA (theoretical explanation of chapter 3, 4, 5). The possibilities and limitations of an ERS infrastructure on the highways between the port of Rotterdam and the port of Antwerp are described in chapter 3. In chapter 4 the zero alternative, the zero+ alternative, the policy scenario and opportunity charging are explained. The effects and input parameters for the SCBA and the SCBA calculations are explained in chapter 5, including assumptions made. The results and the sensitivity analysis of the SCBA are shown in chapter 6. Chapter 7 contains discussion and reflection on the research. Finally, the conclusion is described in chapter 8. An overview of the report can be seen in figure 1.5

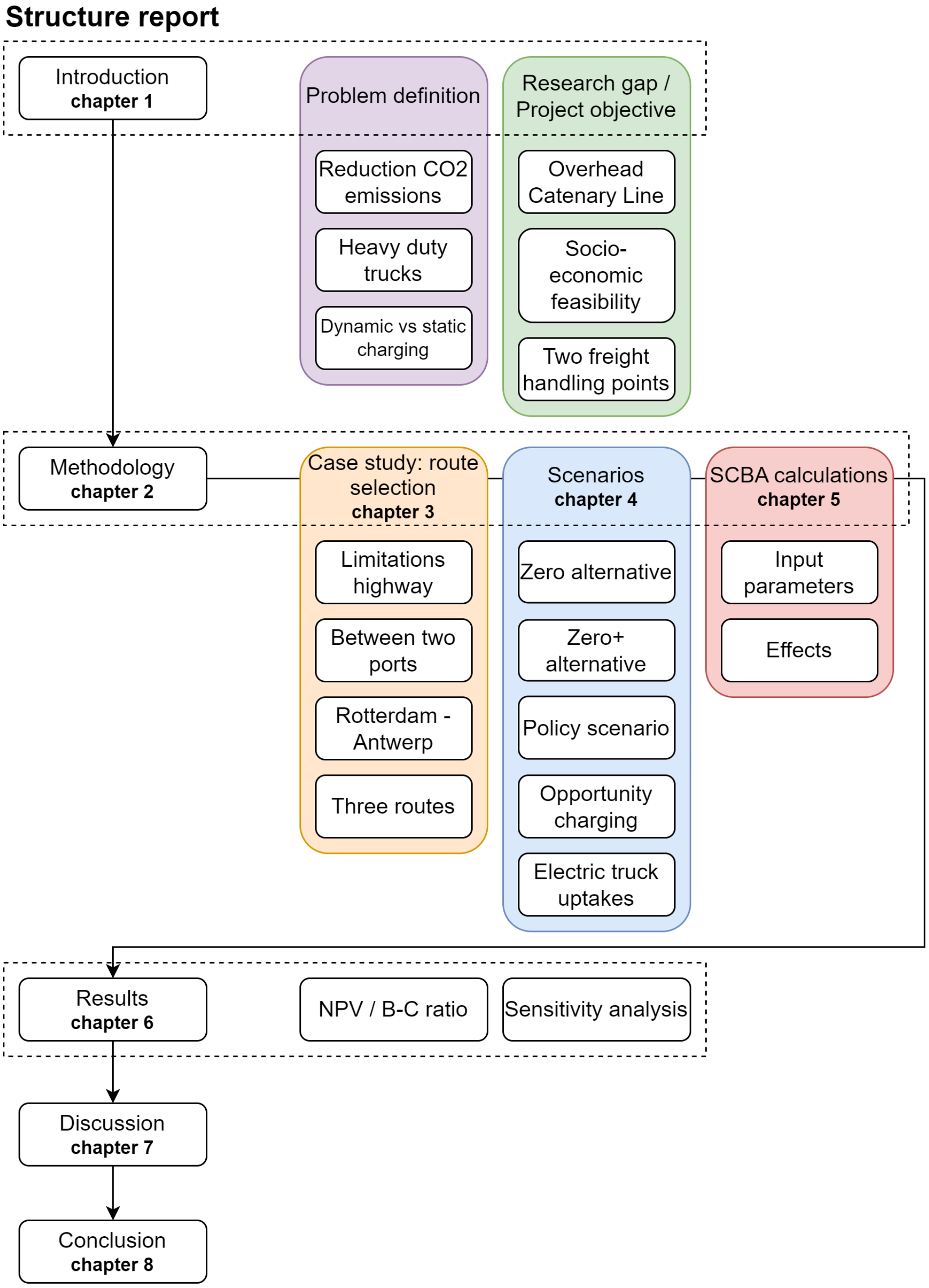

Figure 1.5: Report structure

2

Methodology

In this chapter the methodology used in this research is further elaborated. As described in chapter 1, the socio-economic feasibility of an ERS infrastructure implementation has not been researched in previous studies according a Social Cost Benefit Analysis (SCBA). In addition, studies towards the implementation of an ERS infrastructure often includes entire networks. A shorter route is not researched in depth much (as explained in chapter 1), especially not on routes between two freight handling points. Besides, in previous researches, the ERS infrastructure costs have been included as one cost component. The components of the ERS infrastructure have been split in this research, to test the different lifetime of the ERS infrastructure elements in the sensitivity analysis. The SCBA is performed according 'Algemene leidraad voor Maatschappelijke kosten-baten analyse' (Romijn and Renes n.d.) (English translation: General guidance for Social cost-benefit analysis). In figure 2.1, the structure of this chapter is summarized.
In section 2.1 the Social Cost Benefit Analysis is described. Section 2.2 explains the contribution of the research towards previous researches.

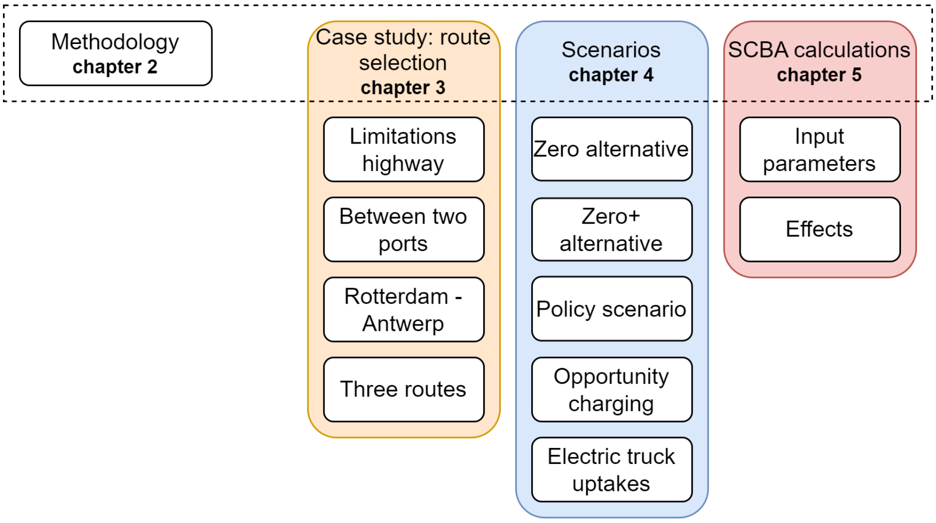

Figure 2.1: Methodology structure

2.1. Social Cost Benefit Analysis (SCBA)

The main method performed in this research is the Social Cost Benefit Analysis (SCBA). A SCBA is often used in the policy processes and political decision making, by testing a policy measure or policy alternative. By monetizing as much effects as possible, arising from the policy measure, the pros and cons can be balanced to create a clear overview in supporting the decision making. In a SCBA a longer time span is included, this visualizes the effects of projects over the coming years. By the use of a SCBA, a comparison between different scenarios is made considering the socio-economic feasibility. All welfare and environmental effects are taken into account in the research. Not all social factors are monetized. Factors which cannot be monetized are uncertainties to the research and are included in the conclusion (Romijn and Renes n.d.).

2.1.1. Case study and alternatives

The first three steps within a SCBA are the problem statement, zero alternative and policy alternatives (Romijn and Renes n.d.). The problem statement, already explained in chapter 1, is formulated as the decarbonization of the heavy duty trucks sector. In this research the solution tested is the conductive Overhead Catenary Line (OCL) system (an Electric Road Systems (ERS) solution). Previous researches mostly focused on the implementation of an ERS infrastructure on an entire network. The start of a European network should begin with a shorter route where a high utilization at starting phase can be ensured (Hacker et al. 2023). Two big influencing locations in the transport sector are the ports of Rotterdam and Antwerp. Freight is transported between these ports every day and from here distributed throughout Europe. The routes between the two ports can be seen as a great starting point for an ERS network in Europe.

Case study

Between the ports of Rotterdam and Antwerp, there are three different routes that can be chosen to transport goods. Not all parts on these three options make it possible to build an ERS infrastructure. In first place, it is needed to visualize the three different routes according its total length, characteristics of the highway (limitations of a highway with regards to ERS infrastructure implementation) and finally the possible ERS infrastructure length. The visualization is done in a couple of steps: literature study, discussion with experts, a field trip and a review on Google Maps. From literature and expert knowledge characteristics came forward that complicate the implementation of an ERS infrastructure. The results for the first part of the SCBA is elaborated in detail in chapter3.

Zero alternative

Within the SCBA a zero alternative is formulated. The zero alternative is described as the original scenario in which no actions are taken (by governmental entities or other stakeholders). The current situation is described and the expected developments take place. In this research it is expected that the number of electric trucks, in this case battery trucks, is increasing over the years. The current number of battery trucks is 0.16% of the total number of trucks in the Netherlands (Netherlands Enterprise Agency 2022). Therefore, it is expected that charging stations are already on the market and is increasing alongside the increase of battery trucks. In this research a theoretical estimation is made of the number of static charging stations. This means that the number of charging stations depends on the number of battery trucks, this is elaborated upon in chapter 5. Besides the zero alternative, a zero+ alternative is conducted. In the zero+ alternative the construction of all charging stations needed in 2054, is finished in 2030. In chapter 4 the implementation of the zero and zero+ alternatives are described depth.

Policy scenario

In the SCBA a policy scenario is described which is tested towards the zero(+) alternative. In the policy scenario a policy measure is taken, which is tested towards zero(+) alternative. Most of the societal effects that arise from the policy measure can be expressed in monetary values. The differences in monetary values between the policy scenario and zero alternative show the effects of the policy measure. The policy scenario in this research is the implementation of an Overhead Catenary Line (OCL) system. This OCL system is an Electric Road System (ERS). Further in the research the term ERS is used for the policy measure. The policy scenario is explained in depth in chapter 4.

Electric truck uptake

Previous studies have shown forecasts on the expected uptake of electric trucks. These uptakes are used in this research as guidelines for the uptake of battery trucks and catenary trucks within the policy scenario and zero(+) alternative. Two papers are considered, namely: Fabius et al (2020) and Tol et al (2022). The forecasts from these researches describe the potential uptake of electric trucks within the heavy duty truck sector. In the report of Fabius et al (2020) a forecast for the implementation of Zero Emission (ZE) trucks within the Netherlands is made, see figure 2.2. The uptake of heavy duty trucks in Fabius et al (2020) consists of battery trucks and hydrogen trucks. The battery trucks are seen as the most economic attractive solution within Fabius et al (2020), compared to hydrogen trucks. In this research hydrogen trucks are not taken into account, only the comparison is made between diesel, battery and catenary trucks. In the report of Tol et al (2022), the term 'opportunity charging' is used, this means that electric trucks are able to charge its battery entirely at least once a day.

Different uptakes are used in the calculations of this research. In chapter 4, the uptakes are described. Besides, the term 'opportunity charging' from the report of Tol et al (2022) is explained in depth and how this has been applied in this research.

Table 2.1: Papers used for electric truck uptakes

Source	Reason
Fabius, Aldenkamp, and Sloten 2020	Forecast for the uptake of electric trucks in combination with hydrogen trucks if no policies are taken
Dennis Tol et al. 2022	Includes 'opportunity charging', which can be obtained by the implementation of ERS

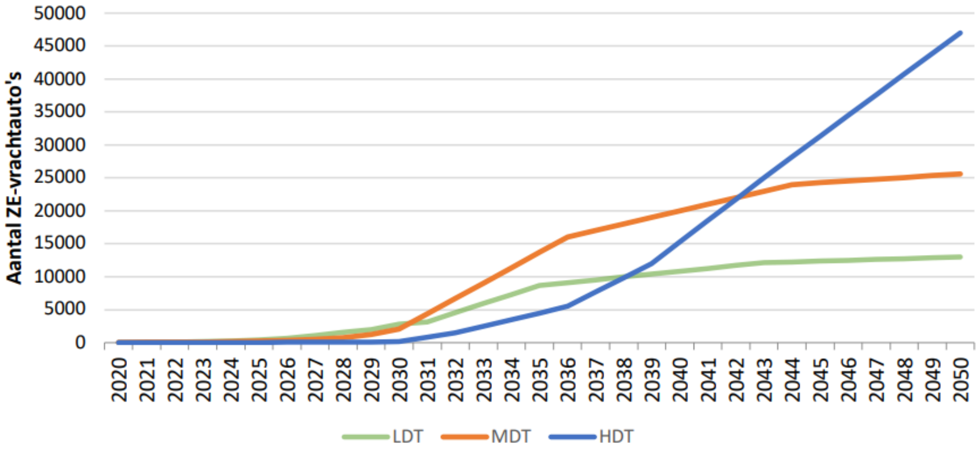

Figure 2.2: Uptake forecast (Fabius, Aldenkamp, and Sloten 2020)

2.1.2. Social costs and benefits

Step four and five are the determination of the social costs and benefits. The complete set of social costs and benefits can be divided into two effects: the direct effects and the indirect effects.

Direct effects are the effects that are directly related to the policy measure that is taken in the policy scenario. These effects consists of the social costs and benefits that occur towards the market the measures are taken into.

The opposite of direct effects are the indirect effects, these effects are working on markets outside of the market the implementation is taken in. These effects are not directly related to the policy measure, but arise indirectly.

Besides the direct and indirect effects, the calculations in the SCBA need other input parameters. These input parameters are not an effect of the policy measure, but enhance or diminish the direct effects.

Direct effects

The cost elements used in previous researches towards ERS are estimates and assumptions made by companies. The range for the different cost elements (Sundelin et al. 2018) can vary significantly, meaning that there is no single cost for the implementation of an ERS infrastructure (PIARC 2023). A large number of variable factors are involved in the calculations, such as the traffic flows and construction lifetime.

In this research a combination of different papers, expert knowledge and historical data for the Netherlands (inflation percentage) has been used as direct effects and input parameters (variables). The variables in the model can be adjusted to other country specific variables or a different case study. The direct effects can be divided into two parts, the infrastructure elements and the truck elements.

The infrastructure cost for the zero(+) alternative consists of the charging station infrastructure cost and the yearly cost for connection to the power supply network. To test the sensitivity of the elements within different lifetime within the charging station infrastructure, the following variables are taken into account: 'Energy feeding point', 'Connection power network construction', 'Power electronics' and 'Transformer'. Besides these four elements within the charging station infrastructure, four variables are added to perform the calculations: 'Other project costs', 'Maintenance chargers', 'Truck per charger per day', and 'Chargers per station'.

Besides the construction and yearly costs for the infrastructure, yearly costs have to be paid to connect each charger to the power supply network. The calculation for these costs consists of the following three elements: 'Standing charge', 'Contracted power' and 'Maximum power'.

Within the policy scenario the ERS infrastructure cost are included as well. The infrastructure construction consist of six elements: 'Energy feeding point', 'Connection power network construction', 'Sub-stations', 'Poles', 'Catenary' and 'Safety barriers'. The perform the calculations, the following four variables are needed: 'Other project costs', 'Maintenance construction parts', 'Maintenance safety barriers' and 'Distance between sub-stations'.

In chapter 5 the variables for the charging stations infrastructure cost, yearly cost for connection to the power network and the ERS infrastructure cost are explained in more depth.

The second element within the SCBA calculations are the truck elements. Within the zero(+) alternative, the two truck types are diesel trucks and battery trucks. In the policy scenario the truck types are extended with catenary trucks. The truck components used for all trucks are the 'Purchase cost', 'Maintenance cost' and 'Residual value'. The truck components are extended with the 'Battery cost' for the battery trucks, and extended with 'Battery cost' and 'Pantograph cost' for the catenary trucks. The maintenance cost are yearly, the purchase cost (including battery and pantograph) and residual value are included after the lifetime of the truck has been reached.

Each type of truck consumes it own type of energy. The energy consumption for diesel trucks is expressed in 'Diesel consumption' and 'Diesel cost'. The calculations for the energy consumption of the battery trucks consist of 'Electricity consumption' and 'Electricity cost charger'. For the calculation of the catenary trucks, more elements are needed. Catenary trucks use electricity directly, but also charge their batteries during transportation. The elements needed are: 'Electricity consumption', 'Electricity cost ERS', 'Percentage connected to ERS' and 'Fully charged trucks'. A description of the elements can be seen in chapter 5.

From 2026 an onwards, trucks transporting on highways in the Netherlands do have to pay charge per kilometer (Rijksoverheid 2023). In this research it is assumed that trucks have to pay this amount already starting in the year 2025. Electric trucks get a discount on the price per kilometer. This results in two elements: 'Diesel truck charge' and 'Electric truck charge'. Besides this truck charge per kilometer, trucks have to buy the Eurovignet each year.

The fourth and final part within the truck elements, are the CO_2, NO_x and PM_v emissions. From the report of de Bruyn et al (2023), the 'CO_2 emission cost', 'NO_x emission cost' and 'PM_v emission cost' have been obtained. The CO_2 emission per truck is different for diesel, battery and catenary trucks. The quantity of CO_2 emissions is calculated based on the energy consumption of the truck type and the carbon foodprint (Carbon Foodprint 2023). The NO_x emission and PM_v emission per truck are calculated according Klein et al (2020). For these two emissions, the difference is made between diesel trucks and electric trucks. Meaning that the NO_x and PM_v emissions for battery trucks equals the emissions of catenary trucks.

The complete overview of the variables used in the calculations are summarized in table 5.2 in chapter 5. The sources used for the data collection of the direct effects and input parameters (all variables) will be mentioned in chapter 5 as well. In total 20 sources have been used for the set up of the input variables in this research.

Because the case study is about the routes between the port of Rotterdam and the port of Antwerp, two countries have been involved in the research. Due to different regulations within countries, other cost elements could arise (for example truck charge). Most kilometers of the three routes are located in the Netherlands, therefore it is chosen to calculate with values counted for in the Netherlands.

Input parameters
Parameters needed for the calculations of the SCBA which are not direct or indirect effects of the policy measure, are included as input parameters. The input parameters are described in detail in chapter 5:

- Mean truck traffic;
  This includes the mean number of trucks according the three alternative routes. The mean number of trucks is calculated according figures obtained via INWEVA (GeoWeb 5.5 n.d.).
- Distance per route;
  The distance of the routes are the total length between the truck parking in the port of Rotterdam and the Deurganck terminal in the port of Antwerp. In chapter 4 a more detailed explanation is given.
- Possible ERS distance per route;
  Via visual inspection on the three alternative routes and literature/expert knowledge, the lengths on the routes are gathered where it is possible to implement an ERS infrastructure.
- Yearly truck growth;
  The mean number of trucks is increasing each year. This is included in the yearly calculation of the total truck cost.
- Trips per day;
  It is assumed that the trucks included in this research travel the route between the port of Antwerp and the port of Rotterdam a couple of times per day.
- Transporting days per year;
  Trucks are not transporting each day of the year. From Tol et al (2023) the number of days is used on which transport trucks act.

SCBA calculations
The monetized direct effects and the input parameters form the core of the calculations within the SCBA. The formulas needed for the calculations are shown and explained in chapter 5. A SCBA model is constructed in Excel to complete the calculations and finally come to the results.
To visualize the effects of a policy measure over the coming years, a longer life span is included in a SCBA. In this research the time span of the research is 30 years. The ERS infrastructure is expected to be recouped in 30 years.

2.1.3. Results SCBA

The outcome of the SCBA represents the different social costs an benefits for the policy scenario compared with the zero alternative. In the future years, money will have a different value from what it is at this moment in time. To express the money in the base year, the future investments are calculated back to the Net Present Value (NPV) in the base year with use of the discount rate. In this research the standard discount rate of 2.25% per year is applied, this value is applied to all type of policy changes (Rijksoverheid 2020). Other impacts towards the discount rate, for example by a world war, is not taken into account in this research.
The results consist of two main contributors: the truck costs and the infrastructure costs. The truck costs relates to the transport companies. In the results the truck costs have been split into nine topics: Truck investment delta (related to purchase), Truck maintenance delta (related to maintenance), Truck residual value delta (related to residual value), Truck energy cost (related to energy consumption and energy cost), CO_2 cost delta (related to CO_2 emissions and energy consumption), NO_x cost delta (related to NO_x emissions), PM_v cost delta (related to PM_v emissions), Truck charge delta (related to truck charge and Eurovignet) and Truck tariff ERS (related to tariff ERS and total energy consumption). The nine topics are described in detail in chapter 5, and the relation of the nine topics towards the direct effects and input parameters is elaborated. Within each of these nine topics, the difference between the policy scenario and the zero(+) alternative is shown in the final results. The difference is calculated over the entire truck fleet in the scenarios over the time span of the research (30 years). Due to the implementation of the ERS infrastructure, these nine truck topics are affected, a delta is arising between the scenario with policy measure and without the policy measure.

Governmental entities or private investors contribute in the project regarding the infrastructure costs. Within the policy scenario the infrastructure costs consist of the ERS infrastructure in combination with a small number of charging stations for the battery trucks. The infrastructure cost within zero(+) alternative only a consist of the infrastructure costs of charging stations. In the final results the infrastructure costs are expressed as 'Infrastructure costs delta', which includes the difference between the total infrastructure cost of the two scenarios.

For the final calculation of the NPV results and B-C ratios the truck cost are summed up in combination with the infrastructure costs.

Net Present Value (NPV) and Benefit-Cost (B-C) ratio

The values is presented as the Net Present Value and the Benefit-Cost ratio. The NPV is the quantitative result of the SCBA (N. Mouter 2012), a positive NPV means that the policy scenario is welfare enhancing (Niek Mouter 2021). A B-C ratio higher than 1 implies that the policy scenario is welfare enhancing and that the policy scenario is a good solution towards the problem. The formulas for the calculations of the NPV and B-C ratio are described in chapter 5, the final results for the NPV results and B-C ratios are visualized in chapter 6.

Sensitivity analysis

Sensitivity analysis is a method to test the influence of the included variables towards the outcome of the project. With the variation in the direct effects and input parameters, the robustness and reliability of the results can be assessed. In the sensitivity analysis, most variables are changed by -10% and +10%. The variables including a lifetime, distance between sub-stations, emission cost and number of chargers per station are not tested by changing its values with -10% and +10%. Fixed values for testing will be used instead, as will be explained in chapter 5. The results for the sensitivity will be shown and interpreted in chapter 6.

Secondly, the five most influencing variables are studied in more depth. From the sensitivity analysis the relation between the five most influencing variables and the NPV results are interpreted.

The final step in the sensitivity analysis tests the sensitivity of multiple variables combined. In this step the eight most influencing variables are taken into account.

2.2. Contribution towards previous researches

As mentioned earlier in this chapter, the research gap within literature on ERS studies is the study towards a Social Cost Benefit Analysis. Besides, ERS infrastructure cost is used as one cost, despite the different lifetimes of the components. In this study the different components are taken into account and the lifetimes are tested in the sensitivity analysis.

To start of an European ERS infrastructure network should start with a point-to-point route between two freight handling points (Hacker et al. 2023). In this research the case study port of Rotterdam - port of Antwerp is studied. The transporting trucks ('shuttle' trucks) between the two ports could guarantee a high utilization of users from the start already. Shuttle trucks play a vital role within the implementation of an ERS infrastructure between the port of Rotterdam and the port of Antwerp. In this research the catenary trucks traveling between the two ports have been assumed to be shuttle trucks.

3

Case study: route selection

In this chapter the overhead catenary line infrastructure is explained with its characteristics. In section 3.1 the infrastructure of an ERS system is described and special constructions on highways are explained and graded with it difficulty for ERS implementation. In section 3.2 the three alternatives routes are visualized with its special constructions and starting point and ending point. Finally, in section 3.3 the possible lengths for an ERS infrastructure on the three alternatives routes between the ports of Rotterdam and Antwerp is shown and is used as input for the SCBA calculations in chapter 5.

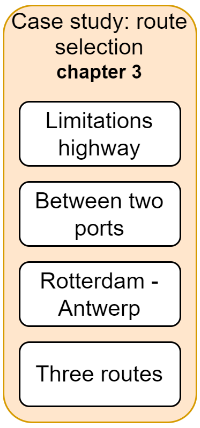

Figure 3.1: Case study: route selection structure

3.1. ERS infrastructure

An conductive overhead catenary line infrastructure is one of the solutions towards the decarbonisation of the heavy duty truck sector. The ERS infrastructure gives the transport companies the option to buy catenary trucks, instead of diesel/battery trucks, and to charge the battery of the truck while driving. The catenary truck consists of a small battery, to fulfill the short distance when not connected to the ERS infrastructure, and a pantograph, to charge and drive electric when connected to the ERS infrastructure. The pantograph is constructed on top of the cabin and can automatically unfold and fold when detecting the catenary lines. The truck driver is also able to unfold and fold the pantograph when overtaking or leaving the highway.
These catenary lines are above the most outer lane of the highway, on which the transporting trucks most of the time drive. Via a hanging construction and poles alongside the highway, the catenary line is spanned above the highway, the construction can be seen in figure 3.2 (Jöhrens et al. 2022). The catenary lines are powered with electricity by sub-stations alongside the highway. These sub-stations are connected to the power supply network of the country to be able to fulfill the needs of the catenary trucks. The number of sub-stations is related to the number of trucks using the ERS infrastructure as power supply, this will be explained further on in chapter 5.

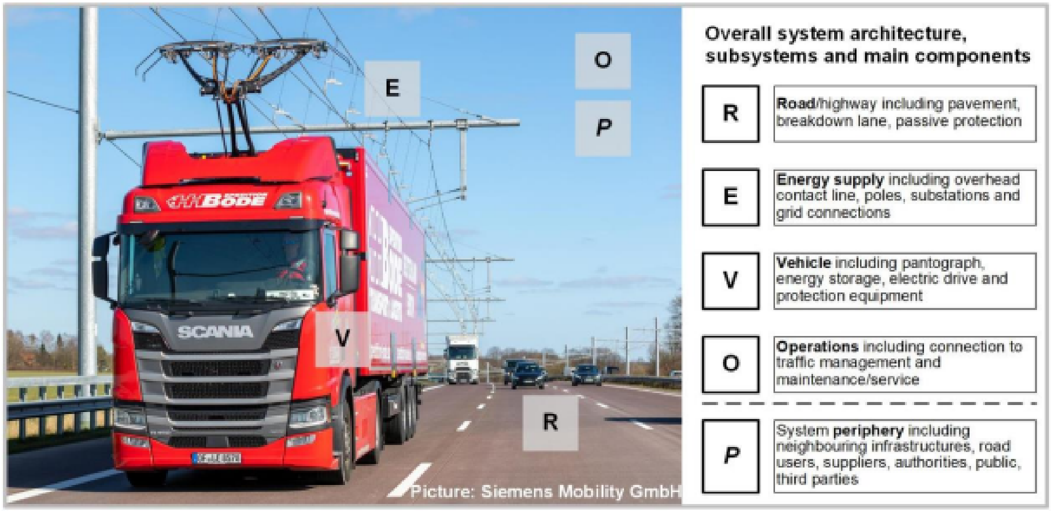

Figure 3.2: ERS construction components (Jöhrens et al. 2022)

3.1.1. Highway special constructions

Highways mostly are mostly located in areas with few surroundings, at these locations the ERS infrastructure can be constructed close by the most outer lane of the highway, as can be seen in figure 3.2 (Jöhrens et al. 2022). Besides these relative simple construction locations, highways often cross special highway construction. These special construction are summarized in table 3.1. The special constructions are graded in table 3.1 and are explained afterwards (++: possible, +: possible but extra conditions, +-: possible but extremely difficult, - impossible for now). The locations, where it is impossible for now or extremely difficult, are not included in this research. Consequently, the ERS infrastructure is divided into segments when crossing a tunnel, bridge or level crossing. Trucks will than make use of the battery it is equipped with.

Table 3.1: Difficulty implementation ERS infrastructure for special highway constructions

Highway element	Difficulty implementation ERS infrastructure
On- and off-ramps	++
Weaving section	++
Lane endings	++
Tunnels	-
Bridges	-
Level crossings	+-
Overpasses	+
Service areas and other road-side provisions	+
Safety barriers	++

On- and off-ramps

To enter or leave the highway on- and off-ramps are connected to the highways. The ERS infrastructure is possible to be build within the highways sections. The construction is still on the outer side of the highway, as shown in figure 3.2, but the span width of the construction has to be longer for the duration of the on- or off-ramp. In figure 3.3 the construction above an off-ramp can be seen.

Weaving sections and lane endings

Weaving sections occur when an on-ramp and an off-ramp come together. Same as for the on- and off-ramps, the span width of the construction increases for the duration of the weaving section. For lane endings the span width is bigger as well, the construction is similar to the one presented in figure 3.3.

Figure 3.3: ERS construction located at an off-ramp (Google Maps n.d.)

Tunnels and bridges
Tunnels and bridges which the highway crosses are left out of the scope for this research. ERS infrastructure has not been tested yet in tunnels and on bridges with a long span width (Siemens n.d.). At these locations it is not possible to build sub-stations for the power supply, within longer tunnels and longer bridges this can lead to difficulties in the implementation.

Level crossings
At level crossings where highways come together, it is extremely difficult to construct an ERS infrastructure. The combination of the ERS infrastructure, weaving sections and roads crossing the highway makes it hard to realize. Therefore these locations are left out of the research.

Overpasses
On the national roads in the Netherlands many overpasses can be counted. To construct an overhead catenary line below an overpass, enough space is needed. The minimal height of the overpass should be at least 4.7 meters (Siemens n.d.Siemens, n.d.). A way to visualize the height difference of an overpass, a lidar scan can be used in combination with pictures from a camera. By linking the two obtained images, the heights can be visualized. Due the construction of the overpass and landslide, caused by the daily traffic and groundwater flows, there are differences in height, see figure 3.4. Since the trucks are travelling on the most right lane, from the center line the overpass the distance should be at least 4.7 meters. In dangerous situations the trucks do also have to be able to evade danger, while connected to the overhead catenary lines with their pantographs. Therefore this method scan a block of 5 meters in width (from the center line 2.5 meters in both ways), in which the minimal height of the overpass should be at least 4.7 meters.

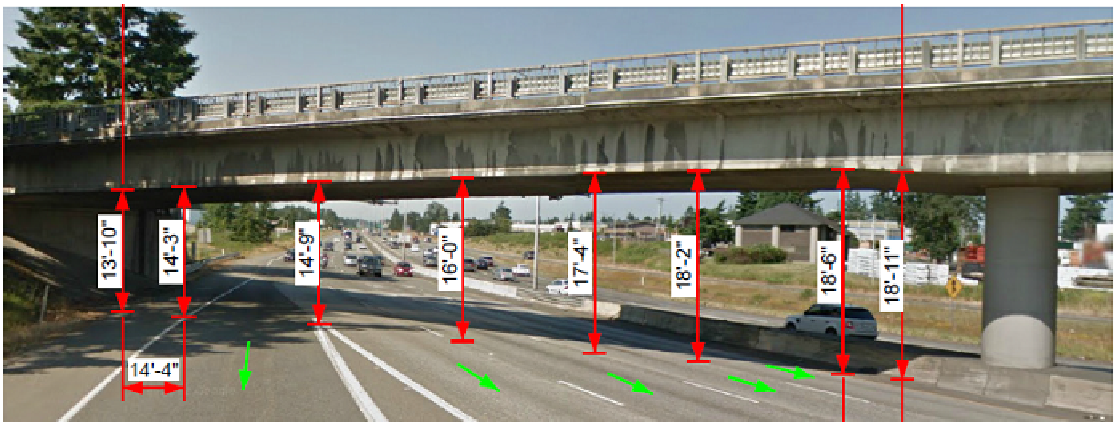

Figure 3.4: Different heights overpass (Webinar n.d.)

Service areas and other road-side provisions
Alongside the highways also other construction can be found, for example gas stations. These constructions make it impossible to construct the poles of the ERS infrastructure on the outer side of the highway. As can be seen in figure 3.5, the pole construction can also be implemented in the median of the highway. The span width will longer compared to the rest of the construction, because the catenary line still is hanging above the most outer lane of the highway. Due to the long span width, the foundation of the construction underneath the poles have to be robuster and will therefor be more costly.
Besides the longer span width at locations where the construction is in the median, at locations with a double on- or off-ramp, the construction will have a longer span width as well. At these locations the pole construction is on the outer side of the highway.

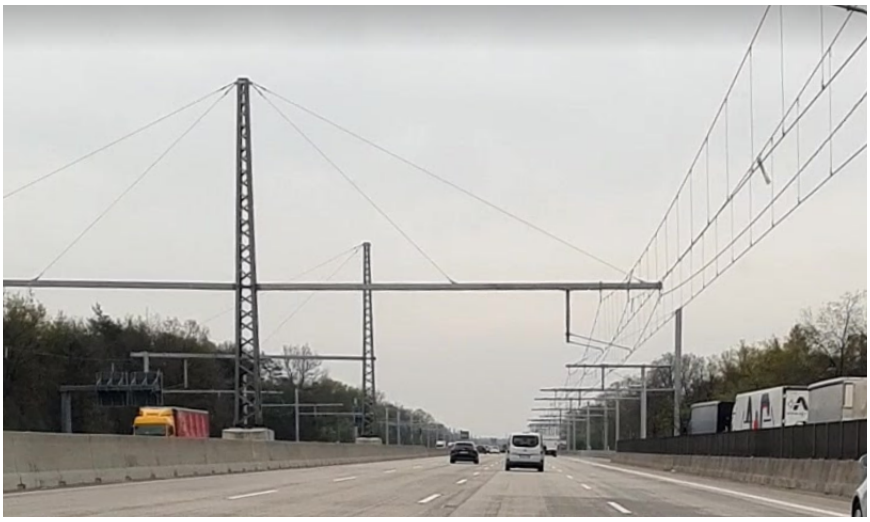

Figure 3.5: ERS construction located in the median of the highway (Google Maps n.d.)

Safety Barriers
Besides the distances for the possible overhead catenary line systems, the model also accounts the distances on safety barriers which obliged characteristics for an ERS system. According the laws in the Netherlands it is obliged to build safety barriers in front of constructions alongside highways. From the most outer road marking, there should be a obstacle free zone of 13 meters. When building an obstacle within this zone, a safety barrier is needed (VeiligeBerm n.d.; SWOV 2017).

3.2. Three alternative routes

Truck traffic between the port of Rotterdam and the port of Antwerp do have three different routes as options, from now on called the Western, Middle and Eastern routes (see figure 3.6). The starting point in the port of Rotterdam is chosen to be the **Truckparking Rotterdam**, in the port of Antwerp the starting point is **MPET K1742 Deurganck Terminal**.

The Western route consists of four different national roads, in the Netherlands the A29, A59 (small part) and A4, and in Belgium the A12. On the A29 the route is crossing the Heinenoordtunnel and the Haringvlietbrug, follow up by passing Bergen op Zoom on the A4. This Western route enters/leaves the port of Rotterdam from the east and enters/leaves the port of Antwerp from the west.

Secondly, the Middle route includes the national roads A16, A17, A58 (small part) and A4 (small part) in the Netherlands and the A12 in Belgium. This route crosses the river Oude Maas via a tunnel and crosses the Moerdijkbrug. The most northern part of the route passes by Dordrecht. Followed up by passing by Roosendaal and meets the Western route at Bergen op Zoom. From Bergen op Zoom in south direction the Western and Middle routes have an overlap.

On the third route, the Eastern route, also overlap can be seen. This route overlaps with the Middle route in the most northern part (besides Dordrecht on the A16). After crossing the Moerdijkbrug (travelling from Rotterdam to Antwerp), the Middle route goes to the A17 at the crossing and the Eastern route continues on the A16. After the A16, only national road in the Netherlands, the national roads in Belgium in this route are the E19 and A12. Other than the Western and Middle routes, the Eastern route enters/leaves Antwerp from the east.

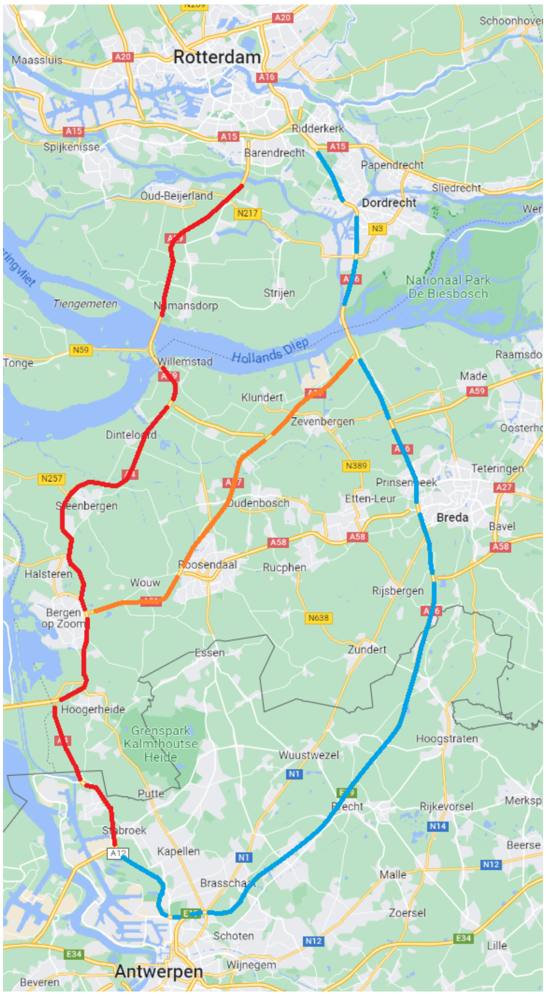

Figure 3.6: Three route alternatives between port of Rotterdam and port of Antwerp (Google Maps n.d.)

3.3. Distance of possible ERS infrastructures

The overhead catenary line system is already being tested in different countries, like the ELISA pilot in Germany. From these pilots it comes forward that it is possible to build the system alongside most of the routes. In the SCBA model, the results for the total distances for possible implementation of the overhead catenary line system can be seen. All parts are included except for level crossings, the Heinenoordtunnel, the Haringvlietbrug, the tunnel (Middle and Eastern routes) and the Moerdijkbrug. Since it is not tested yet on bridges (with an larger span width) and tunnels and it is difficult to construct it at level crossing, these are not included in this research.

From the Truckparking Rotterdam towards the three alternative routes a short trip on the A15 is needed, this distance will not be taken into account as potential road for an overhead catenary line system. Same counts for the first/last part of the route near the MPET K1742 Deurganck Terminal, trucks will travel here on the R2, which is not included for a potential construction of the infrastructure.
The Western route between the two ports is in total 93,4 kilometers, from which **61 kilometers** can be implemented with an overhead catenary line. Within the Middle route (total 107 kilometers), the implementation distance is **62 kilometers**. On the Eastern route the implementation distance is **72 kilometers**, the entire route is 114 kilometers.

4

Scenarios

In this chapter the zero alternative, zero+ alternative and policy scenario are explained. One policy scenario is tested towards the zero and zero+ alternatives, namely the implementation of an ERS infrastructure. In section 4.1 the zero alternative is described, additionally the zero alternative is extended to a zero+ alternative. The policy scenario, which is tested towards the zero alternative and the zero+ alternative, is described in section 4.2. The comparison between the policy scenario and the zero(+) alternative is researched with different uptakes of electric trucks over the years. Finally, in section 4.3, an overview is given with the different uptakes taken into account in this research (between the different comparisons).

The time span of the research is 2025-2054 (30 years). The ERS infrastructure construction is assumed to be finished in 2030. Besides the catenary and diesel trucks in the policy scenario, also battery trucks are included.
In this research three alternatives routes are taken into account, the characteristics and fleet sizes of these routes are explained in chapter 3. The fleet sizes differ per route, which influence the construction costs and truck components costs within the zero alternative, zero+ alternative and the policy scenario.

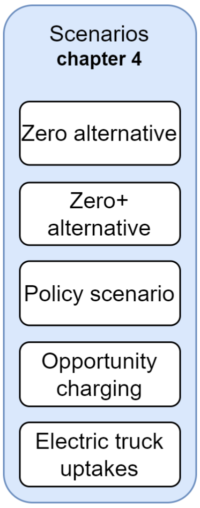

Figure 4.1: Scenarios structure

4.1. Zero alternative

The zero alternative is the alternative in which no specific measures are taken by government or public investors. This means that most trucks are transporting by the use of an industrial combustion engine (ICE), in combination with the recent uptake of electric trucks. 0.16% Of the total number of trucks within the Netherlands is driving on an electric basis, namely as battery trucks. Since the electric trucks are already upcoming, the uptake of battery trucks (as electric trucks) is taken into account within the zero alternative. For the uptake of battery trucks within the zero alternative, the uptake forecast of the research of Fabius et al (2020) is used. In the year 2023 the electric truck fleet is 0.16%, followed up by a 3% in 2030 and a 46% of electric trucks in 2054 (since the number of electric trucks is 50.000 of a total fleet of 110.000), see figure 2.2. Between 2030 and 2054 the uptake of battery trucks is assumed to be linear, in reality the uptake can be different due to many influencing factors (for example the battery price changes). To foresee the total number of battery trucks from electricity, the uptake of static charging stations depends on the uptake of the battery trucks.
Assumptions have been made towards the charging stations, namely: one charger can charge 15 trucks per day, and one charging stations consists of 8 Megawatt chargers. Megawatt Charging Stations (MCS) are not on the market at the moment, it is assumed that this new method of charging is available from 2025 and onwards. With the implementation of new battery trucks in a year, new charging stations are being build, this will be explained in chapter 5.

4.1.1. Opportunity charging

The comparison is made between on the one hand the zero/zero+ alternative, with on the other hand the policy scenario. In this comparison all scenarios do have the possibility of opportunity charging, this means that all trucks are able to charge the battery completely once a day (minimum). It is assumed that, because of the possible opportunity charging, the uptake for all scenarios is equal. The uptake is linear and is as follows: 0.16% (2023) - 19% (2030) - 44% (2040) - 81% (2054). This uptake is obtained based on the report of Tol et al (2022), see figure 4.2. They do include two subsidies within the opportunity charging, namely: 'AanZET' (English: Start) and 'Terugsluis' (English: Return). In this research subsidies are not taken into account, therefor the uptake within opportunity charging is chosen to be the linear part of the report of Tol et al (2022) (the years after the subsidies). The years 2030 - 2040 have been taken into account, which has a linear increase of around 25% per 10 years. The uptakes for the zero alternative and the policy scenario with opportunity charging can be seen in Appendix A. For the policy scenario the catenary trucks percentage of 60% is shown, besides this number of catenary trucks also percentages of 50% and 65% are tested.

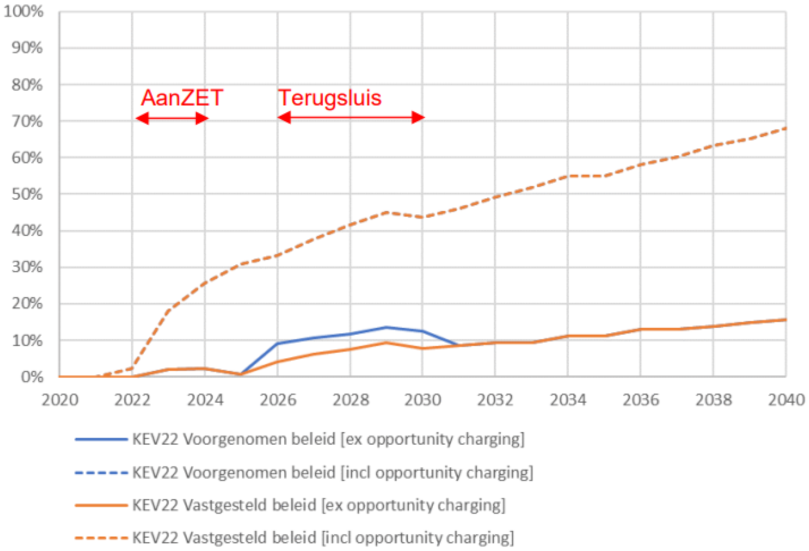

Figure 4.2: Opportunity charging uptake according Dennis Tol et al. 2022

4.1.2. Zero+ alternative

Besides testing the policy scenario towards the zero alternative, the policy scenario is tested towards a zero+ alternative. The difference between the zero and zero+ alternatives is the construction of the charging stations. In the zero alternative the uptake of charging stations goes along with the uptake of battery trucks, each year new charging stations are built to fulfill the power demand from the battery trucks. In the zero+ alternative all charging stations are constructed in the year 2030. The number of charging stations build depends on the number of battery trucks in the year 2054. This means that the investment cost for charging stations are higher compared to the zero alternative (construction cost + maintenance cost), but this also results in a quicker uptake of battery trucks. The uptake of battery trucks in the zero+ alternative starts with 0,16% in 2023 and grows to 3% in 2030. Till 2030 the uptake is the same as the zero alternative, since the construction of the charging stations is finished in 2030. The uptake from 2030 till 2054 is tested with different values in this research, varying from a battery truck percentage in 2054 of 60%, 70% and 80%.

4.2. Policy scenario

The policy scenario tested in this research contains the implementation of an ERS infrastructure on the three routes between the port of Rotterdam and the port of Antwerp. The possibilities for implementation of an ERS infrastructure on the three routes are explained in chapter 3. Besides the diesel trucks and battery trucks driving between the two ports, the ERS infrastructure makes it possible to transport by catenary trucks. The uptakes within the policy scenario exist of diesel trucks, battery trucks and catenary trucks. Since the construction of the ERS infrastructure is finished in 2030 (implementation of catenary trucks in 2031), the uptake of battery trucks till 2030 is assumed to be equal to the uptake in the zero alternative: linear increase between 2023 (0,16%) and 2030 (3%). For the uptake from 2030 till 2054, different values are tested in the research. The uptakes tested are: 70% and 80% electric trucks in 2054, consisting of 40%, 50% or 60% of catenary trucks. In chapter 6 the most expected uptakes are show and explained in depth, the other results can be seen in Appendix C.

4.3. Overview uptakes

The overview table show the uptakes taken into account in the calculations. The first row of the table shows the year. In the second row the uptake percentage within zero(+) alternative are shown. Within the third and fourth (only first and third comparisons) rows the different uptakes are shown according the policy scenario. This means that for the first comparison four uptakes have been tested. Three times resulting in 70% electric trucks in 2054 and once resulting in 80% electric trucks in 2054.
All results can be found in Appendix C. In chapter 6 three uptakes are analyzed and described in detail. For the first comparison this will be the policy scenario in which 50% of catenary trucks are included. In the second comparison the percentage of catenary trucks is 60%. Within the third comparison the percentage of catenary trucks is 50% in the policy scenario.

First comparison: policy scenario and zero alternative

Table 4.1: Uptakes of electric trucks taken into account, comparison between the policy scenario and the zero alternative

Year	2023	2030	2040	2054
Zero alternative	0.16%	3%	14%	46%
Policy scenario	0.16%	3%	31%	70% (40%, 50%, 60% catenary trucks)
Policy scenario	0.16%	3%	35%	80% (50% catenary trucks)

Second comparison: policy scenario and zero alternative (with opportunity charging)

Table 4.2: Uptakes of electric trucks taken into account, comparison between the policy scenario and the zero alternative (including opportunity charging)

Year	2023	2030	2040	2054
Zero alternative	0.16%	19%	44%	81%
Policy scenario	0.16%	19%	44%	81% (50%, 60%, 65% catenary trucks)

Third comparison: policy scenario and zero+ alternative

Table 4.3: Uptakes of electric trucks taken into account, comparison between the policy scenario and the zero+ alternative

Year	2023	2030	2040	2054
Zero+ alternative	0.16%	3%	31%	70%
Policy scenario	0.16%	3%	31%	70% (40%, 50%, 60% catenary trucks)
Policy scenario	0.16%	3%	35%	80% (50% catenary trucks)

5

SCBA calculations

In this chapter the SCBA model is explained. In section 5.1 an overview is given of the input parameters that are used in the calculations. These input parameters are described and divided into direct effects (section 5.2), indirect effects (section 5.3) and other input parameters (section 5.4). The calculations, which are the core of the SCBA model, are explained in section 5.5. Finally, in section 5.6 extra calculations are shown.

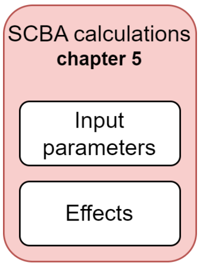

Figure 5.1: SCBA calculations structure

5.1. Overview parameters

In table 5.1 the input parameters are summarized, in combination with the source of the parameter value which have been used for the calculations of the ERS infrastructure cost, the static charging station infrastructure cost and the connection to the power supply network yearly cost. Since the cost parameters for the ERS infrastructure and the charging station infrastructure is from the years 2017, inflation is used to calculate the value as it is worth today. The 27% is the CPI (Customer Price Index) inflation percentage for industrial goods since 2017 (CBS 2023). By multiplying the cost value for 2017 by the inflation percentage, the cost parameters for the infrastructures are calculated for the current year. It is assumed that all infrastructure elements increased with this inflation percentage, in reality the different infrastructure elements can have another inflation rate. The infrastructure cost are direct effects on the policy measure, the description of the parameters listed in table 5.1 are described in section 5.2 (direct effects). The stakeholders involved in the infrastructure costs are the governmental entities or private investors.

Table 5.1: Direct effects used for calculation infrastructure elements

Direct effect	Unit	Value	Lifetime	Source
Inflation	%	27%	-	CBS 2023
Infrastructure ERS				
Energy feeding point	euro/connection	15,000	-	Stütz et al. 2017
Connection power network construction	euro/connection	25,000	-	Stütz et al. 2017
Sub-station (3MVA)	euro/connection	900,000	25	Stütz et al. 2017
Poles (50 meters distance)	euro/pole	10,000	30	Stütz et al. 2017
Catenary	euro/meter	300	12	Stütz et al. 2017
Safety barriers	euro/meter	100	25	Stütz et al. 2017
Other project costs	%	10%	-	Stütz et al. 2017
Maintenance construction parts	%	5%	-	Deshpande et al. 2023
Maintenance safety barriers	%	1%	-	assumption
Distance between sub-stations	km	3,5	-	Siemens n.d.
Infrastructure charging station				
Energy feeding point	euro/connection	15,000	-	Stütz et al. 2017
Connection power network construction	euro/connection	25,000	-	Stütz et al. 2017
Power electronics (1,000 kW)	euro/charger	149,000	12	Mareev and Sauer 2018
Transformer	euro/charger	45,000	25	Mareev and Sauer 2018
Other project costs	%	10%	-	Stütz et al. 2017
Maintenance chargers	%	5%	-	Deshpande et al. 2023
Truck per charger per day	trucks	50	-	Burges and Kippelt 2021
Chargers per station	chargers	8	-	assumption
Connection power network yearly cost				
Standing charge	euro/year	441	-	Enexis 2023
Contracted power	euro/kW/year	16.99	-	Enexis 2023
Maximum power	euro/kW/month	1.83	-	Enexis 2023

In table 5.2 the input parameters for the truck calculations can be seen. The battery prices are not shown in the table, this is because of the decrease in battery price over the years. The battery price is described further on in this chapter and visualized in figure 5.2. The purchase price of the battery and catenary trucks are without the battery and pantograph.

The ERS tariff is also not mentioned in the table. This is because the tariff is calculated over the total energy used by trucks connected to the ERS infrastructure. This means that the ERS tariff changes if a different uptake is tested in the research.

Two different calculations have been used, one for the CO_2 emissions and another calculation for the NO_x and PM_v emissions. These truck component parameters are described in more detail in section 5.2 (direct effects).

The stakeholder involved in the truck costs are the transport companies. The transport companies have to invest in new and current trucks, have to pay for the energy consumption of the trucks and are responsible for the emission cost of the trucks.

Table 5.2: Direct effects used for calculation truck elements

Direct effect	Unit	Value				Source
Truck components						
Year		**2025**	**Yearly**	**2030**	**Yearly**	
Purchase diesel truck	euro	150,500	+1,500	158,000	+1,100	D. Tol et al. 2023
Purchase battery truck	euro	265,500	-15,300	189,000	-2,800	D. Tol et al. 2023
Purchase catenary truck	euro	175,500	-8,700	132,000	-1,300	D. Tol et al. 2023
Pantograph cost	euro	20,475	-585	17,550	-585	Ainalis, Thorne, and Cebon 2020
Battery size battery truck	kWh	600	-	-	-	assumption
Battery size catenary truck	kWh	150	-	-	-	assumption
Maintenance diesel truck	euro/year	7000	-	-	-	D. Tol et al. 2023
Maintenance battery truck	euro/year	3500	-	-	-	D. Tol et al. 2023
Maintenance catenary truck	euro/year	3000	-	-	-	assumption
Residual value truck	%	10%	-	-	-	Chang 2020
Energy consumption and cost						
Diesel truck	kWh/km	2.63	-	-	-	Deshpande et al. 2023
Battery truck	kWh/km	1.44	-	-	-	Deshpande et al. 2023
Catenary truck	kWh/km	1.3	-	-	-	Deshpande et al. 2023
Percentage connected to ERS	%	80%	-	-	-	Deshpande et al. 2023
Fully charged trucks	%	25%	-	-	-	Deshpande et al. 2023
Diesel cost	euro/liter	1.98	-	-	-	ANWB 2023
Electricity cost charger	euro/kWh	0.19	-	-	-	D. Tol et al. 2023
Electricity cost ERS	euro/kWh	0.13	-	-	-	Deshpande et al. 2023
Truck charges						
Diesel truck charge	euro/km	0.155	-	-	-	Rijksoverheid 2023
Electric truck charge	euro/km	0.03	-	-	-	Rijksoverheid 2023
Eurovignet	euro/year	1,327	-	-	-	Rijksoverheid 2023
Emissions						
	Unit		**Lower**	**Modest**	**Upper**	
CO$_2$ cost	euro/kg	-	0.05	0.13	0.16	Bruyn et al. 2023
NO$_x$ cost	euro/kg	-	18.3	29.9	44.1	Bruyn et al. 2023
PM$_v$ cost	euro/kg	-	41.4	69.3	97.9	Bruyn et al. 2023
CO$_2$ diesel truck	kg/kWh	0.68	-	-	-	Deshpande et al. 2023
CO$_2$ battery truck	kg/kWh	0.53	-	-	-	Deshpande et al. 2023
CO$_2$ catenary truck	kg/kWh	0.48	-	-	-	Deshpande et al. 2023
NO$_x$ diesel truck	g/km	2.1	-	-	-	Klein et al. 2020
NO$_x$ electric truck	g/km	0.61	-	-	-	Klein et al. 2020
PM$_v$ diesel truck	g/km	0.06	-	-	-	Klein et al. 2020
PM$_v$ electric truck	g/km	0.03	-	-	-	Klein et al. 2020

Besides these two tables with input parameters for the infrastructure and truck elements calculations, input parameter have been used on the three route alternatives. The figures used are shown in table 5.3. The input parameter below are discussed in section 5.4 (other input parameters).

Table 5.3: Input parameters used for the number of trucks and the alternative route lengths

Input parameter	Unit	Value	Source
Route alternative			
West distance	km	93.4	Google Maps n.d.
West ERS distance	km	61	visual inspection
Middle distance	km	107	Google Maps n.d.
Middle ERS distance	km	62	visual inspection
East distance	km	114	Google Maps n.d.
East ERS distance	km	72	visual inspection
Number of trucks			
West mean	vehicles	4,000	GeoWeb 5.5 n.d.
Middle mean	vehicles	4,300	GeoWeb 5.5 n.d.
East mean	vehicles	6,800	GeoWeb 5.5 n.d.
Truck growth	%/year	1.5%	CBS n.d.
Trips per day	trips	4	assumption
Days per year	days	260	D. Tol et al. 2023

5.2. Direct effects

The direct effects are the effects that arise from the implementation of a measurement in the policy scenario, these effects are directly related to the measure taken. Firstly, this includes the infrastructure cost. Without the implementation of an ERS infrastructure, the infrastructure cost would only exist of charging stations infrastructure cost. Since the ERS infrastructure is being build, the ERS infrastructure cost are directs effects, but also the change in charging station infrastructure cost. Due to the ERS infrastructure construction, the number of charging stations needed in future years is limited. The different infrastructure also results in a different yearly maintenance cost and a different yearly cost for the connection to the power supply network. All elements, included in the infrastructure cost, will be explained in this section.

Besides the direct infrastructure effects, the ERS implementation affects the heavy duty truck elements, catenary trucks differ from battery trucks. Both trucks have a battery, but in case of the catenary truck the size of the battery is limited. The catenary truck contains a pantograph on the cabin to connect to the ERS infrastructure. All truck elements together result in a different purchase price, maintenance cost, residual value, energy consumption and emissions. These effects, which all can be monetized, are elaborated on further in this research. Besides these monetized effects, other directs effects are summarized.

Investment cost infrastructure

The construction of the ERS infrastructure can be obtained with an investment, which would not have happened in the zero alternative. Due to the investment in ERS, the number of charging stations can be limited. The construction of charging stations is therefore effected by the policy scenario.

ERS infrastructure

In the policy scenario, tested in this research, the construction of an ERS infrastructure is finished in 2030. The distance of the ERS infrastructure is dependent on the route alternative. The construction cost of the ERS infrastructure is split into multiple elements, this is because of the different lifetimes of the elements. The lifetime is taken into account to test the different elements in the sensitivity analysis. The elements taken into account are: Energy feeding point, Connection to the power network (construction), Sub-stations, Poles, Catenary, Safety barriers and Other project costs. For the calculation the costs from the research of Stutz et al. (2017) are used, shown in table 5.4.

Table 5.4: Construction cost ERS infrastructure in 2017 (Stütz et al. 2017)

Element	Unit	Cost [euros]	Lifetime [years]
Energy feeding point	euro/connection	15,000	-
Connection power network short	euro/connection	25,000	-
Sub-station (3 MVA)	euro	900,000	25
Poles (50 meter distance) (both ways)	euro/pole	10,000	30
Catenary (both ways)	euro/meter	300	12
Safety barriers (both ways)	euro/meter	100	25
Other project costs (planning etc.)	%	10%	-

The different lengths of the three alternative routs result in different construction cost for the ERS infrastructure. As described in chapter 3, the potential lengths for the three routes are: West 61 kilometers, Middle 62 kilometers and East 72 kilometers.

Besides the length of the potential ERS infrastructure, the distance between the sub-stations is important. The shorter the distance between the sub-stations, the more trucks can make use of the ERS infrastructure . With a distance of 7 km in between the sub-stations, the maximum utilization on the route is 1 truck/km per direction. A distance of 3.5 km results in a maximum utilization of 3 truck/km per direction, and a distance of 1.75 km results in a maximum utilization of 7 truck/km per direction (Siemens n.d.). In this research a distance of 3.5 kilometers is chosen in between the sub-stations, it is assumed that the number of trucks using the ERS infrastructure can be fulfilled with this distance between the sub-stations.

The power supply of the sub-stations have be assumed to be 3 MVA (MegaVoltAmpere), which is 3,000 kW. As shown in table 5.4, the cost for a 3 MVA sub-station is 900,000 euros. Per MVA the cost for the sub-stations is 300,000 euros. It is assumed that with a power supply of 3 MVA of the sub-stations, all trucks using the ERS infrastructure can be supplied with electricity.

Static charging station infrastructure

Besides the ERS infrastructure cost, the infrastructure cost for static charging stations is needed for the calculation. Within the zero alternative and the zero+ alternative, all battery trucks will be powered by these static charging stations. As result of the ERS infrastructure in the policy scenario, less static charging stations are needed in the policy scenario. Since the construction of the ERS infrastructure is finished in 2030, battery trucks are already appearing on the market till 2030. The uptake of the battery trucks continues after 2030, also in the policy scenario, so static charging stations are still constructed needed in the policy scenario. The construction of a charging station consists of the following elements: Energy feeding point, Connection to power network (construction), Power electronics, Transformer and Other project costs. In table 5.5 the used costs can be seen. Again, the lifetimes for the power electronics and transformer are taken into account to test the sensitivity of the infrastructure parameters in the end.

Table 5.5: Construction cost charging station (Mareev and Sauer 2018; Stütz et al. 2017)

Element	Unit	Cost [euros]	Lifetime [years]
Energy feeding point	euro/connection	15,000	-
Connection power network short	euro/connection	25,000	-
Power electronics	euro/station	149,000	12
Transformer	euro/station	45,000	25
Other project costs (planning etc.)	%	10%	-

It is assumed that from 2025 the chargers are Mega Watt Chargers (MCS), which is 1,000 kW. Each charger is able to charge 50 battery trucks per day (Burges and Kippelt 2021), and the number of chargers per charging station is assumed to be 8 MCS. The calculation of the total number of chargers, and so the number of charging stations, depends on the number of battery trucks. The number of battery trucks depends on the uptake of electric trucks, which is described in chapter 2 and chapter 4. The calculation for the number of charging stations is as follows (the number of chargers is rounded up):

$$\text{Number of static chargers} = \frac{\text{Number of battery trucks}}{\text{Charging capacity static charger}} \tag{5.1}$$

$$\text{Number of charging stations} = \frac{\text{Number of static chargers}}{\text{Number of charger per charging station}} \tag{5.2}$$

Maintenance cost infrastructure

Yearly maintenance cost for ERS infrastructure differ from the yearly maintenance cost for charging stations. The difference between the two maintenance costs is included in the calculation for the SCBA over 30 years.

ERS infrastructure

Multiple elements within the ERS infrastructure need yearly maintenance. The constructed parts that need maintenance are the sub-stations, poles, catenary and safety barriers. The yearly maintenance costs for the sub-stations, poles and catenary is 5% of the construction cost of the element (Deshpande et al. 2023). For the safety barriers the yearly maintenance cost are assumed to be 1% of the construction cost.

Static charging station infrastructure

Same as the maintenance for the construction elements of the ERS infrastructure, static charging stations need yearly maintenance cost, which is 5% as well. The maintenance cost are calculated over the power electronics and transformer.

Yearly cost connection to power supply network

As described within the ERS infrastructure and the static charging station infrastructure, costs are included for the construction of the connection to the power supply network (Energy feeding point and Connection to power network). Since the connection to the power supply network is per sub-station (3,000 kW) and per charger (1,000 kW), differences in the total connections occur within the policy scenario compared to the zero alternative. The differences between the two scenario is taken into account.

Besides the construction costs for making the connection, the connection to the power network contains of three elements: Standing charge, Contracted power cost and Maximum power cost (Enexis 2023). These three elements are on a yearly basis. The standing charge costs are 441 euro per year, the contracted power cost are 16.99 euro/kW per year and the maximum power cost are 1.83 euro/kW per month. In table 5.6 the yearly cost for connection to the power supply network are shown for a sub-station (3,000 kW) and for a static charger (1,000 kW).

Table 5.6: Yearly connection cost for connection to power supply network for a sub-station and a static charger based on Enexis 2023

Element	Sub-station cost [euro]	Static charger cost [euro]
Standing charge [yearly]	441	441
Contracted power cost [yearly]	50,970	16,990
Maximum power cost [yearly]	65,880	21,960

Truck elements cost

Within the zero alternative two types of trucks are acting: diesel and battery trucks. In the policy scenario, three types of trucks are acting: diesel, battery and catenary trucks. These three different trucks are equipped with different elements, this results in a different purchase price, maintenance cost and residual values. The price differences results in a delta for the SCBA.
Values for the the calculations of the purchase price of the vehicles are obtained by the research of Tol et al (2023). The diesel truck purchase price increases slightly over the years. The purchase cost of the battery truck consist of the purchase cost and the battery cost. Catenary trucks do consist of the purchase cost, battery cost and the pantograph cost (Ainalis, Thorne, and Cebon 2020). The purchase prices for the truck types and the pantograph cost are shown in table 5.7.

Table 5.7: Truck purchase cost based on D. Tol et al. 2023

Truck type	Purchase cost 2020	Cost 2020-2030	Purchase cost 2030	Cost 2030-2054
Diesel	143,000	1,500	158,000	1,100
Battery	342,000	-15,300	189,000	-2,800
Catenary	219,000	-8,700	132,000	-1,300
Pantograph	23,400	-585	17,500	-585

Currently the battery price is still high, but the battery price is expected to drop. The battery price forecast from Tol et al (2023) is used in this research. In Tol et al (2023), the battery price forecast is based on research of BNEF (BNEF 2021). Besides the extrapolations based on the past, they do include future developments as well, for instance such as the integration of battery cells directly into the vehicle chassis which results in further cost reductions (D. Tol et al. 2023), see figure 5.2. Due to the direct use of electricity, the catenary truck is able to contain a small battery, which will lead to a lower battery purchase cost. In this research the battery capacity chosen for the battery trucks has a capacity of 600 kWh and the capacity of the catenary truck battery is 150 kWh. The lifetime for all trucks is set to be 8 years (CBS n.d.) before selling it to another country or industry. Therefore, the residual value is taken into account and is 10% of the purchase price of the truck. The diesel trucks can be sold to another country, for the battery and catenary truck this will probably not be the case. It is assumed that these trucks are sold to other industries which can use the truck elements for other purposes. The residual values have been equated for convenience. As said, the maintenance is lower for battery and catenary trucks compared to diesel trucks. Diesel trucks have a yearly maintenance cost of 7,000 euro, battery trucks of 3,500 euro/year (D. Tol et al. 2023). It is assumed that the catenary truck have a yearly maintenance cost of 3,000 euro, a catenary truck needs specific maintenance for the pantograph.

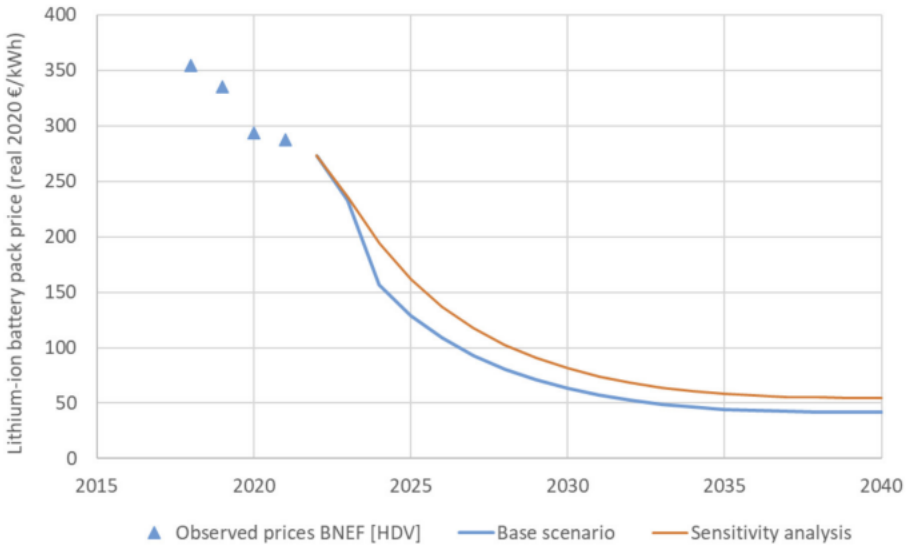

Figure 5.2: Battery price expectation based on BNEF 2021 (D. Tol et al. 2023)

Energy consumption and cost

In this research the Well-to-Wheel (WTW) energy of the trucks is taken into account. Each truck types (diesel, battery and catenary) has its own energy consumption. In this research the energy consumption per truck type is taken as one value for the entire time span of the SCBA. Due to the different energy consumption and the different lengths of the routes, the policy scenario is expected to have a positive effect according the energy consumption, which is included in the NPV and B-C ratio calculations.

Diesel trucks have an energy consumption ($\mathrm{E}_{c,DT}$) of 2.63 kWh/km and battery trucks an energy consumption ($\mathrm{E}_{c,BT}$) of 1.44 kWh/km, these calculations are based on Deshpande et al (2023) (see figure 5.3):

$$\mathrm{E}_{c,DT}\ [\mathrm{kWh/km}] = \frac{\mathrm{WTW\ E}_{c,DT}}{\mathrm{v}} = \frac{263}{100} = 2.63\ \mathrm{kWh/km} \tag{5.3}$$

$$\mathrm{E}_{c,BT}\ [\mathrm{kWh/km}] = \frac{\mathrm{WTW\ E}_{c,BT}}{\mathrm{v}} = \frac{144}{100} = 1.44\ \mathrm{kWh/km} \tag{5.4}$$

With WTW as Well-To-Wheel and v as the speed. The electricity input ($\mathrm{E}_{i,CT}$) by the ERS infrastructure, electricity consumption ($\mathrm{E}_{c,CT}$) and the electricity storage ($\mathrm{E}_{s,CT}$) can be calculated with the following formulas (Deshpande et al. 2023):

$$\mathrm{E}_{i,CT}\ [\mathrm{kWh/km}] = \frac{\mathrm{E}_{t,CT}\ [\mathrm{kW}]}{\mathrm{v}} * (1 - \frac{\text{Fully charged trucks [\%]}}{2}) \tag{5.5}$$

$$\mathrm{E}_{i,CT}\ [\mathrm{kWh/km}] = \frac{300}{100} * (1 - \frac{25\%}{2}) = 2.6\ \mathrm{kWh/km} \tag{5.6}$$

$$\mathrm{E}_{c,CT}\ [\mathrm{kWh/km}] = \frac{\mathrm{WTW\ E}_{c,CT}}{\mathrm{v}} = \frac{130}{100} = 1.3\ \mathrm{kWh/km} \tag{5.7}$$

$$\mathrm{E}_{s,CT}\ [\mathrm{kWh/km}] = \mathrm{E}_{i,CT} - \mathrm{E}_{c,CT} = 1.3\ \mathrm{kWh/km} \tag{5.8}$$

Electricity per truck ($\mathrm{E}_{t,CT}$) is the total power the truck receives from the ERS infrastructure, $\mathrm{E}_{i,CT}$ is the electricity input into the catenary truck, $\mathrm{E}_{c,CT}$ is the energy consumption of the catenary trucks and $\mathrm{E}_{s,CT}$ is the storage (charging) capacity of the catenary trucks. It is assumed that 25% of the connected trucks is already fully charge. The result is the electricity in kWh/km that the truck receives (2.6 kWh/km). The truck needs 130 kW directly for driving with a speed of 100 km/h, the direct electricity consumption is 1.3 kWh/km. This means that 1.3 kWh/km can be used to charge the battery. When the truck is fully charged, it only takes out the electricity for direct use

Trucks do have to connect to the infrastructure and disconnect (while overtaking or crossing a level crossing). Therefore, it is assumed that trucks are connected to the infrastructure 80% of their ride. This 80% value is used in the calculations for the SCBA, which will be explained in section 5.5.

The energy consumptions of the diesel, battery and catenary trucks are monetized by multiplying the energy consumption by the energy cost. For diesel the energy cost of 1.98 euro/Liter is used (ANWB 2023). For the electricity cost for battery trucks the cost is 0.19 euro/kWh (Dennis Tol et al. 2022), the charging station infrastructure is included. The cost for ERS electricity used in this research is 0.13 euro/kWh, the ERS infrastructure cost are excluded and calculated separately. The calculation for the ERS tariff is explained in the next subsection.

Truck cost per kilometer

To drive on European highways, truck charge have to be paid per year or per kilometer. Each truck needs a Eurovignet to drive on European highways, the costs for this Eurovignet are 1,327 euro/year. Besides the Eurovignet, other truck charge have to be paid, these truck charge are country specific. In Belgium the truck charge are 0.183 euro/km, no differences between diesel or electric trucks. In the Netherlands the truck charge (truck tax, in dutch called 'Vrachtwagenheffing') is going to be implemented in 2026 (Rijksoverheid 2023). The cost for a diesel truck is 0.155 euro/km. Electric trucks benefit from a discount of 81%, this results in the cost for electric trucks of 0.03 euro/km. In the comparison between the policy scenario and the zero alternative, this results in a difference which is included in the SCBA.

Table 5.8: Emissions cost per kilogram (Klein et al. 2020)

Emissions	**Lower limit**	**modest limit**	**Upper limit**
CO_2	0.05	0.13	0.16
NO_x	18.3	29.9	44.1
PM_v	41.4	69.3	97.9

Besides these truck charge, within the policy scenario trucks have to pay a tariff for using the ERS infrastructure. The height of the ERS tariff cost differ per route alternative due to the different ERS lengths and the number of catenary trucks using the ERS infrastructure. The calculation for the ERS tariff per kilometer is based on the total construction cost for the ERS infrastructure over the life span of 30 years, including maintenance and yearly connection to power supply network cost. This means that the total investment in the infrastructure cost is recouped in 30 years. The investment for the time span of 30 years is to be paid by the users of the ERS infrastructure. To come to the ERS tariff, the total construction cost is divided by the total energy consumption of all catenary trucks over the time span of 30 years. This means that each catenary truck pays for the energy it consumed while connected to the ERS infrastructure, the formula is as follows:

$$\text{ERS tariff} = \frac{\text{Total construction cost ERS infrastructure}}{\text{Total energy consumption connected to ERS infrastructure}} \tag{5.9}$$

Emissions and emission cost

One of the main objectives of the implementation of battery and catenary trucks is the decarbonization of heavy duty trucks. This is mainly done by decreasing the CO_2 emissions. In this research the CO_2 emissions per truck are first expressed in kilograms. With the kilograms per truck, the total of kilograms CO_2 can be calculated for the total number of trucks in the zero and zero+ alternatives and the policy scenario. Besides the kilograms CO_2, the total CO_2 emissions are monetized according the cost value assigned by de Bruyn et al (2023). Each year CE Delft presents a handbook for environmental prices. The prices are per kilogram of the emissions accounted for. The main calculation are performed by means of the modest cost value. To test the sensitivity in the sensitivity analysis, the lower and upper values are tested. Besides the cost for CO_2 emissions, shown table 5.8, the costs for NO_x and PM_v emissions are also shown. These two emissions have also been taken into account in this research. The CO_2 emission cost are expected to increase each year with a percentage of 3.5% (Klein et al. 2020). The CO_2 emissions have been calculated according Deshpande et al (2023) and the Carbon footprint for the Netherlands (Carbon Foodprint 2023). The WTW principle is taken into account, which can be seen in figure 5.3. At the wheels it is expected that all type of trucks need 100 kWh to drive. For a diesel truck the WTW energy for this movement is 263 kWh, for battery trucks 144 kWh and for catenary trucks the WTW energy needed is 130 kWh. With the combination of figure 5.3 and the value grid electricity CO_2 emissions, the CO_2 emissions for the three type of trucks can be calculated. The production fuel mix factor for the Netherlands is 0.37 kilogram CO_2 per kWh (Carbon Foodprint 2023). The CO_2 emissions per truck per year are calculated with the following formulas.

$$CO_2 \text{ emissions [kg]} = E_c * \text{Trips} * \text{Days} * \text{Distance} * \text{kg } CO_2 \text{ per kWh} \tag{5.10}$$

$$\text{kg } CO_2 \text{ per kWh} = \text{WTW kWh} * \text{Carbon footprint} = \text{WTW kWh} * 0.37 \tag{5.11}$$

Besides the calculations for the total kilograms CO_2, the NO_x and PM_v emissions have been calculated. These calculations are based on the Klein et al (2020) report. In table 5.9 the emission values are given for diesel and electric trucks, this means that the NO_x and PM_v emissions for battery trucks and catenary trucks is equal. With the following formulas the calculations per truck per year for NO_x and PM_v are obtained:

$$NO_x \text{ emissions [kg]} = \frac{\text{WTW } NO_x}{1000} * \text{Trips} * \text{Days} * \text{Distance} \tag{5.12}$$

$$PM_v \text{ emissions [kg]} = \frac{\text{WTW } PM_v}{1000} * \text{Trips} * \text{Days} * \text{Distance} \tag{5.13}$$

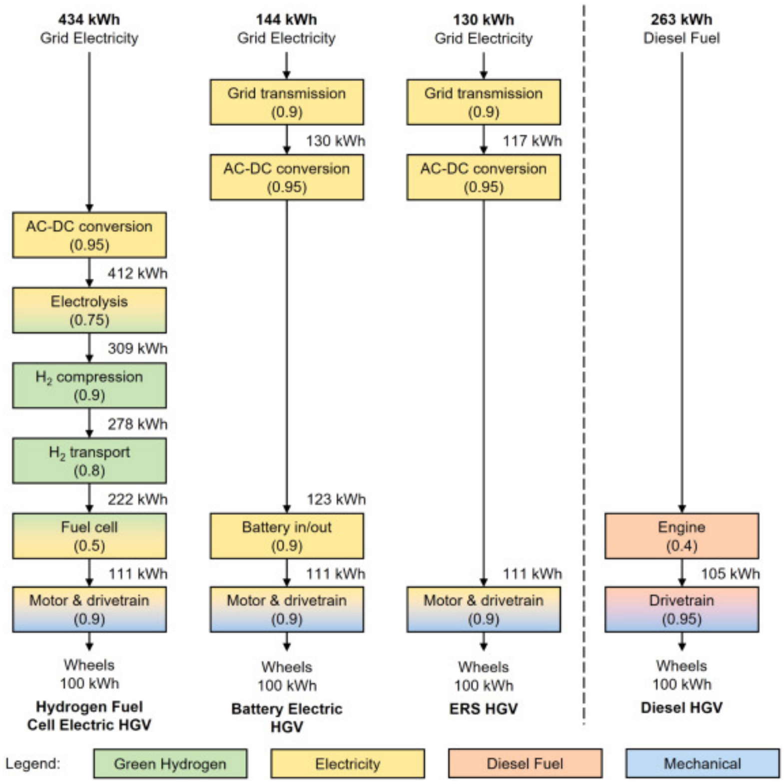

Figure 5.3: Well-To-Wheel energy consumption different truck types (Deshpande et al. 2023)

Table 5.9: WTW emissions [gram/km]

Emission	Diesel truck	Electric truck percentage	Electric truck
NO_x	2.1	29%	0.6
PM_v	0.06	48%	0.03

Non-monetized direct effects

Besides these monetized direct effects, included in the SCBA, there are other direct effects that arise when construction the ERS infrastructure. These other effects can have a positive or negative impact on the outcome:

- Special constructions on the highway adjustments (-)
  Due to the ERS infrastructure implementation some special constructions have to be adjusted to make it possible to implement the ERS infrastructure, this will come with extra costs.

- Travel time savings (+)
  Electric trucks do not have to charge the battery via static charging anymore due to the possibility of dynamic charging of ERS. This will lead to shorter travel times for the trucks, since the trucks do not have to leave the highway for charging, does not need to connect to the charging station and wait while charging the truck.

- Area savings alongside the highway (+)
  Each charging stations needs a place alongside the highway, which is easily reachable. These grounds have to be bought or rented yearly. This leads to large-scale land use to fulfill the needs for electricity. ERS infrastructure needs ground area as well for implementation, but this is limited compared to charging stations. The construction is mostly located alongside the highway, supplemented by sub-stations (for which grounds have to be bought or rented).

- Safety (-)
  The safety of highways is changing by the implementation of ERS. The hanging catenary lines above the highways can break, which will cause serious danger.

- Highway view (-)
  By the ERS construction, the view on the highways is changing.
- Congestion and route shift of trucks (+-)
  It is not known yet what will happen to the traffic on highways after implementation of the ERS infrastructure, especially when ERS is used by high number of trucks. If the construction is build on the Western route, this can result in a route shift of trucks from the Eastern route. This leads to more truck traffic on the Western route, but more available space on the Eastern route.

5.3. Indirect effects

The opposite of the direct effects are the indirect effects. These effects do not have effect of the transport market between the port of Rotterdam and the port of Antwerp. Indirect effects that happen due to the ERS infrastructure implementation are the temporary employment opportunities during construction. Besides the employment opportunities during construction, the yearly maintenance has to be performed by companies from outside the transport market.

Directly, the transport market for transportation between the port of Rotterdam and the port of Antwerp is affected. As described earlier in chapter 1, the implementation of an entire ERS infrastructure network throughout Europe should start on a shorter route. The implementation on these three routes alternatives could eventually evolve to a bigger European network in which, not only the Belgium and Dutch transport markets, the European market is growing as a whole.

The indirect effects mentioned will not elaborated upon further in this research.

5.4. Input parameters

Besides the direct and indirect effects, the calculations for the SCBA need other input parameters. These parameters are not directly effects arising from the policy scenario, but are important. In table 5.3 the other input parameters can be seen, these are:

- Mean truck traffic
- Distance per route
- Possible ERS distance per route
- Yearly truck growth
- Trips per day
- Transporting days per year

The direct effects used in the calculations of the SCBA depend on these input parameters. The ERS infrastructure cost depend on the possible ERS distance on the three alternative routes.

To calculate the total emissions, energy used and truck charge, the mean number of trucks is needed on the three alternative routes. The number of trucks is expected to increase in future years, to take this into account a yearly truck growing percentage is used. The emissions, energy and truck charge do also depend on the distance travelled (route distance), number of trips per day, and number of days per year the truck is transporting. In the next section these parameters are included in the explanation of the formulas 5.14 and 5.15.

5.5. Calculations SCBA: NPV results and B-C ratios

All effects combined finally result in the Net Present Value (NPV) and Benefit-Cost (B-C) ratio for the policy scenario, on the three different routes. Within the calculation of the NPV results and B-C ratios, per route alternatives the infrastructure cost, truck investment cost, truck maintenance cost, truck residual values, truck energy cost, truck CO_2 emissions cost, truck NO_x emissions cost, trucks PM_v emissions cost, truck charge and truck tariff ERS have been calculated. In some calculations, the total travelled distance per year per truck and the total distance connected to the ERS infrastructure are needed, this is implemented with the formulas below:

$$\text{Total distance} = \text{Trips} * \text{Days} * \text{Distance} \tag{5.14}$$

$$\text{Total distance ERS} = \text{Trips} * \text{Days} * \text{Distance}_{ERS} * \text{Percentage connected} \tag{5.15}$$

5.5.1. Infrastructure elements

Charging station cost

The infrastructure cost in the zero and zero+ alternatives consist of the charging station infrastructure cost, maintenance charging station cost and chargers connection to the power supply network construction cost. The charging station infrastructure cost are calculated with the following formulas:

$$\text{Energy feeding point cost} = \text{Cost} * \text{Inflation} * \text{Number of charging stations} * \text{Discount factor} \tag{5.16}$$

$$\text{Power network construction cost} = \text{Cost} * \text{Inflation} * \text{Number of charging stations} * \text{Discount factor} \tag{5.17}$$

$$\text{Power electronics cost} = \text{Cost} * \text{Inflation} * \text{Number of charging stations} * \text{Discount factor} \tag{5.18}$$

$$\text{Transformer cost} = \text{Cost} * \text{Inflation} * \text{Number of charging stations} * \text{Discount factor} \tag{5.19}$$

$$\text{Other project cost} = (\text{Power electronics} + \text{Transformer}) \text{ cost} * \text{Percentage other cost} \tag{5.20}$$

ERS infrastructure cost

These costs for the static charging station infrastructure are also included in the policy scenario. Besides the charging stations cost, the policy scenario contains the ERS infrastructure cost. With use of the following formulas the ERS cost have been calculated:

$$\text{Number of sub-stations} = \frac{\text{ERS length}}{\text{Distance between sub-stations}} + 1 \tag{5.21}$$

$$\text{Energy feeding point cost} = \text{Cost} * \text{Inflation} * \text{Number of sub-stations} * \text{Discount factor} \tag{5.22}$$

$$\text{Power network construction cost} = \text{Cost} * \text{Inflation} * \text{Number of sub-stations} * \text{Discount factor} \tag{5.23}$$

$$\text{Sub-stations cost} = \text{Cost} * \text{Inflation} * \text{Number of sub-stations} * \text{Discount factor} \tag{5.24}$$

$$\text{Poles cost} = 2 * \text{Cost per pole} * \text{Inflation} * \frac{1{,}000}{50} * \text{ERS distance} * \text{Discount factor} \tag{5.25}$$

$$\text{Catenary cost} = 2 * \text{Cost per meter} * 1000 * \text{Inflation} * \text{ERS distance} * \text{Discount factor} \tag{5.26}$$

$$\text{Safety barriers cost} = 2 * \text{Cost per meter} * 1{,}000 * \text{Inflation} * \text{ERS distance} * \text{Discount factor} \tag{5.27}$$

$$\text{Other project cost} = (\text{Sub-stations + Poles+Catenary+ Safety barriers}) \text{ cost} * \text{Percentage other cost} \tag{5.28}$$

Maintenance infrastructure

Each element within the ERS infrastructure and the static charging station infrastructure needs to be maintained each year. Yearly the a percentage of the construction cost is taken into account as the yearly maintenance cost. The maintenance for the safety barriers is calculated separately, since this element needs less maintenance compared to the other elements:

ERS infrastructure maintenance

$$\text{Maintenance ERS} = (\text{Sub-stations+ Poles +Catenary}) \text{ cost} * \text{Percentage maintenance cost} \tag{5.29}$$

$$\text{Maintenance safety barriers} = \text{Safety barriers cost} * \text{Percentage maintenance cost} \tag{5.30}$$

Static charging station infrastructure maintenance

$$\text{Maintenance charging stations} = (\text{Power electronics} + \text{Transformer}) \text{ cost} * \text{Percentage maintenance cost} \tag{5.31}$$

Connection to power supply network yearly

The yearly connection (to the power supply network) for the sub-stations (3,000 kW) and chargers (1,000 kW) contains the three elements: standing charge, contracted power and maximum power. The standing charge is a fixed charge per sub-station or charger. The calculation of the contracted power and maximum power are as follows:

$$\text{Contracted power cost} = \text{Cost} * \text{Power sub-station/charger} \tag{5.32}$$

$$\text{Maximum power cost} = \text{Cost} * \text{Power sub-station/charger} * 12 \text{ months} \tag{5.33}$$

All three elements combined result in the final yearly cost for the connection to the power supply network:

$$\text{Total connection cost} = \sum(\text{Three elements}) * \text{Number of sub-stations/chargers} * \text{Discount factor} \tag{5.34}$$

5.5.2. Truck elements

Truck investment cost

The investment cost for the trucks have been calculated according the purchase prices explained in the formulas below. Per route alternative a different number of trucks is transporting each day. For the west the mean is 4,000, the middle 4,300 and the east 6,800.

$$\text{Purchase diesel truck} = \text{Purchase cost} * \text{Discount factor} \tag{5.35}$$

$$\text{Purchase battery truck} = (\text{Purchase} + \text{Battery}) \text{ cost} * \text{Discount factor} \tag{5.36}$$

$$\text{Purchase diesel truck} = (\text{Purchase} + \text{Battery} + \text{Pantograph}) \text{ cost} * \text{Discount factor} \tag{5.37}$$

With the combination of the purchase cost, the uptake in the scenario and the lifetime of the trucks, the total investment cost can be calculated. The lifetime of each truck is set to be 8 years, this means that the truck is replaced after 8 years, a new investment is done. For diesel trucks it is difficult to tell how old the current trucks are. Therefore, it is assumed that half of the diesel trucks has to be replaced after 4 years and the other is replaced after 5 years. The total investment cost is the sum of the new diesel trucks, the new battery trucks and (in case of the policy scenario) the new catenary trucks.

$$\text{Total investment cost} = \sum(\text{New trucks} * \text{Purchase cost truck}) \tag{5.38}$$

Truck maintenance cost

In the zero and zero+ alternatives, new diesel trucks and battery trucks are in use. In the policy scenario also catenary trucks are in use. The total maintenance cost per year is the sum of the maintenance cost for the diesel, battery and (in case of the policy scenario) catenary trucks.

$$\text{Total maintenance cost} = \sum(\text{Maintenance cost per truck} * \text{Number of trucks}) \tag{5.39}$$

Truck residual value

After 8 years, lifetime of the trucks, the trucks are replaced. The investment cost increase, but the truck which is going out of the system still has its residual value. The residual value is calculated with a percentage of the purchase cost. The total residual value per year consists of the sale of old diesel trucks, old battery trucks and (in case of the policy scenario) old catenary trucks.

$$\text{Total residual value} = \sum(\text{Percentage residual value} * \text{Purchase cost truck}) \tag{5.40}$$

Truck energy cost

Diesel trucks, battery trucks and catenary trucks have a different energy consumption. The total energy consumption in the zero(+) alternative or policy scenario is calculated by the energy consumption per truck times the total number of trucks, per driving engine.

$$\text{Total energy cost} = \sum(\text{Energy consumption per truck} * \text{Total distance} * \text{Number of trucks} * \text{Energy cost}) \tag{5.41}$$

Emissions

The kilograms of emissions per truck are explained in the previous section, these figures per truck are multiplied by the cost and the number of trucks driving in the year (diesel, battery and catenary). The sum of the emissions of the three truck types give the total emission cost per emissions type.

Truck CO_2 emissions cost

$$\text{Total } CO_2 \text{ emission cost} = \sum(CO_2 \text{ emissions per truck} * CO_2 \text{ cost per kg} * \text{Number of trucks}) \tag{5.42}$$

Truck NO_x emissions cost

$$\text{Total } NO_x \text{ emission cost} = \sum(NO_x \text{ emissions per truck} * NO_x \text{ cost per kg} * \text{Number of trucks}) \tag{5.43}$$

Truck PM_v emissions cost

$$\text{Total } PM_V \text{ emission cost} = \sum(PM_v \text{ emissions per truck} * PM_v \text{ cost per kg} * \text{Number of trucks}) \tag{5.44}$$

Truck charge cost

For diesel trucks the truck charge per kilometer are different than for electric trucks in the Netherlands. Diesel trucks pay 0.155 euro/km and electric trucks pay 0.03 euro/km. The total cost for truck charge are calculated by multiplying the cost with the number of trucks. Besides these truck charge, the Eurovignet is added times the number of trucks, the cost for the Eurovignet is the same for all trucks.

$$\text{Total truck charge cost} = \sum((\text{Eurovignet cost} + \text{Truck charge per truck} * \text{Total distance}) * \text{Number of trucks}) \tag{5.45}$$

Truck tariff ERS cost

The ERS infrastructure cost are split into a tariff paid by the users. As explained in the previous section, the tariff for using the ERS infrastructure is the total ERS infrastructure cost divided by the total predicted energy consumption (when connected to the ERS infrastructure) over 30 years. This means that the ERS infrastructure is recouped in 30 years.

$$\text{Total tariff ERS cost} = \sum(\text{Tariff ERS cost} * \text{Total distance ERS} * \text{Number of catenary trucks trucks}) \tag{5.46}$$

5.5.3. NPV and B-C ratio formulas

Finally, the results for the SCBA can be calculated with the formulas for NPV and B-C ratio. The input for the NPV and B-C ratio calculations are the summations for the infrastructure cost and the truck cost. The truck cost consist of: Investment, Maintenance, Residual value, Energy, CO_2 emissions, NO_x emissions, PM_v emissions, Truck charge and Tarif ERS.

$$\text{NPV} = \sum_{t=0}^{n} \frac{CI_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{CO_t}{(1+r)^t} \tag{5.47}$$

In which (Gaspars-Wieloch 2019):

- CI [euro] is the cash inflow (benefit in SCBA)
- CO [euro] is the cash outflow (costs in SCBA)
- t [years] is the time
- Discount factor is $\frac{1}{(1+r)^{(t-1)}}$ with r as discount r
- n is the number of periods

$$\text{B-C ratio} = \frac{\sum_{t=0}^{n} \frac{CI_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{CO_t}{(1+r)^t}} \tag{5.48}$$

In which (CFI n.d.):

- CI [euro] is the cash inflow (benefits or costs in SCBA)
- CO [euro] is the cash outflow (costs in SCBA)
- t [years] is the time
- Discount factor is $\frac{1}{(1+r)^{(t-1)}}$ with r as discount r
- n is the number of periods

5.6. Extra calculations

Total energy consumption

For the calculation of the ERS tariff, the total energy consumption is needed in the policy scenario. Per route alternative and per year, the total energy consumed by all heavy duty trucks is calculated. The total energy consumption is expressed in kWh. A diesel truck consumes 2.63 kWh/km, a battery truck 1.44 kWh/km, and a catenary truck consumes 1.3 kWh/km.

$$\text{Total energy consumption} = \sum(\text{Energy consumption per truck} * \text{Total distance} * \text{Number of trucks}) \qquad (5.49)$$

Truck purchase price over the years

In the beginning, the purchase price for battery trucks is higher compared to diesel trucks. The price gap between the different type of trucks is decreasing over the years. In figure 5.4 the purchase prices for the three different type of trucks are shown, it can be seen that the catenary truck is less expensive than the diesel truck from 2028 and on wards. The purchase price for battery trucks is becoming cheaper than diesel trucks in the year 2039. The purchase prices are used for the calculation of the investment costs, need for the investment savings in the results (chapter 6.

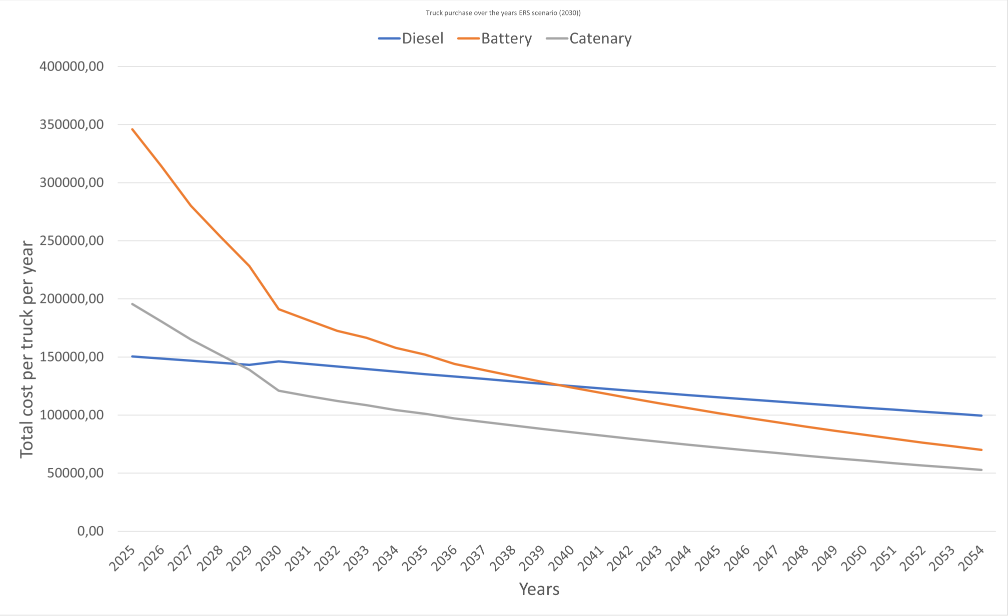

Figure 5.4: Truck purchase prices over the years

Total kilograms of CO_2 emissions

One of the main goals is to decrease the total CO_2 emissions within the heavy duty truck sector. For each year the total kilograms of CO_2 emissions is calculated for the different routes and comparisons. In figure 5.5 the CO_2 emissions can be seen for the zero alternative and the policy scenario for the eastern route. In figure 5.6, the total CO_2 emissions for all trucks is shown in the zero+ alternative and the policy scenario. It can be seen that till 2030 only diesel trucks are still driving, since the ERS infrastructure construction is finished and taken into use in 2030. From 2030 till 2054 the gap between the two CO_2 emissions increases. Within the comparison between the zero+ alternative and the policy scenario, this difference is increasing as well, but the gap between the two scenarios is not as big as in figure 5.5. The total kilograms of CO_2 emissions are calculated used in the calculation of the CO_2 emissions savings needed for the calculation of the NPV outcomes.

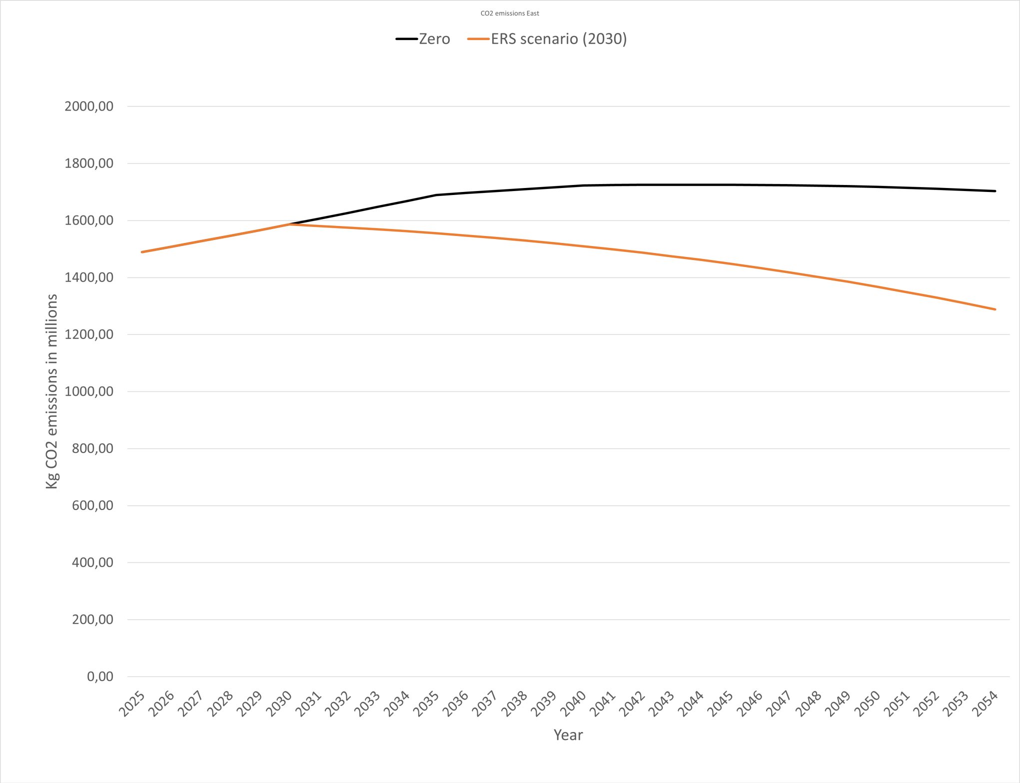

Figure 5.5: CO_2 emissions zero alternative and policy scenario on the eastern route

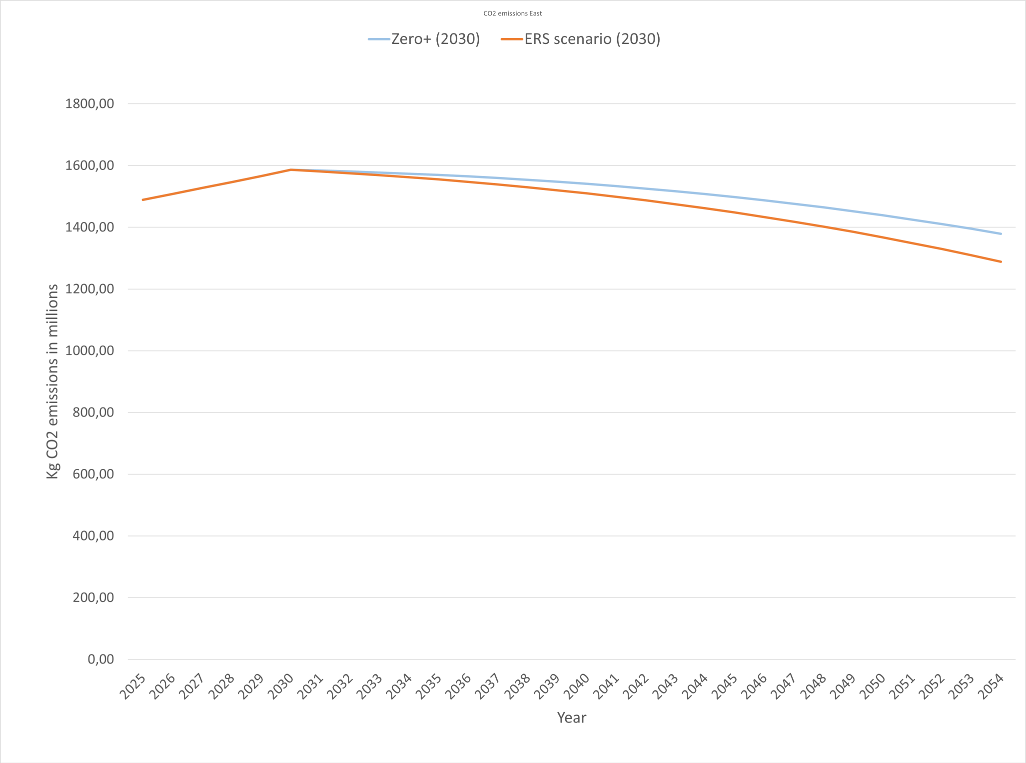

Figure 5.6: CO_2 emissions zero+ alternative and policy scenario on the eastern route

6

Results and sensitivity analysis

In this chapter the results and interpretations of the results are given. The results show the socio-economic feasibility of an ERS infrastructure in the heavy duty truck transportation. In section 6.1 an overview is given of the results. Followed up, in section 6.2 the results are shown for the comparison between the policy scenario and the zero alternative. Section 6.3 shows the results of the policy scenario compared to the zero+ alternative. The results of the opportunity charging comparison can be seen in section 6.4. Lastly, the input parameters are tested on its sensitivity, the results can be seen in section 6.5.

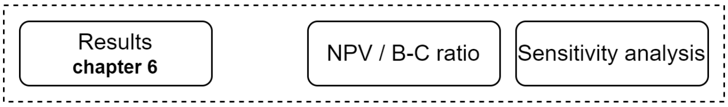

Figure 6.1: Results structure

6.1. Results overview

In table 6.1 the results for the Western route are shown. Table 6.2 show the final results of the comparisons for the Middle route. Thirdly, in table 6.3 the results on the Eastern route can be seen. Within the tables 6.1, 6.2 and 6.3 the first nine components belong to the trucks elements. Truck companies do have to deal with the following the truck elements:

- Truck investment delta:
  All trucks are assumed to have lifetime of 8 years before sold to another country or other industry. By selling the old trucks, new trucks have to be bought, which result in the investment in new trucks. The differences between the total investments made in the policy scenario and the total investments made in the zero(+) alternative (over the 30 year life span) result in the investment savings included in the results.
- Truck maintenance delta:
  Diesel (7,000 euro per year), battery (3,500 euro per year) and catenary (3,000 euro per year) have a different yearly maintenance cost (D. Tol et al. 2023). In the policy scenario the percentage of catenary trucks increases over the years, which result in a lower total maintenance cost. The difference between the total maintenance cost in the policy scenario and the zero(+) alternative are visualized in the maintenance savings.
- Truck residual value delta:
  After the lifetime the trucks are sold to another country or other industry. 10% Of the purchase price of the truck is earned on selling the old trucks. The difference between the policy scenario and zero(+) alternative in selling the old trucks over the 30 years is expressed in the residual values cost.

- Truck energy cost delta:
  Catenary trucks are more economical in consumption compared to battery and diesel trucks. The total energy costs for all trucks in the policy scenario minus the total energy costs for all trucks in the zero(+) alternative result in the energy savings for the research period of 30 years.

- CO_2 cost delta, NO_x cost delta, PM_v cost delta:
  The total costs for CO_2, NO_x, and PM_v emissions are first calculated for the policy scenario and the zero(+) alternative. The difference between the two scenarios for the three emission types have been included in the final calculation of the NPV results and B-C ratios.
  For the NO_x and PM_v emissions, the values will only be shown in the comparison between the policy scenario and zero alternative (unequal uptake). This is because the emissions for catenary and battery trucks are set equal, with an equal uptake the differences between the policy and zero(+) alternative is zero, which can be seen further in this research.

- Truck charge delta:
  Within the comparison between the policy scenario and zero(+) alternative on the truck charge, the same happens as for the NO_x and PM_v emissions. Truck charge have been set to 0.15 euro per kilometer for diesel trucks and 0.03 euro per kilometer for electric trucks. In case of an equal uptake between the scenarios, the difference in truck charge cost is zero.

- Truck tariff ERS:
  The ERS infrastructure implementation is expected to be recouped in 30 years. This means that the users have to pay a tariff for using the ERS infrastructure. In the zero(+) alternative, a tariff for ERS infrastructure is not included, since the ERS is not applied. Therefore, the difference between the policy scenario and the zero(+) alternative is shown as the ERS tariff calculated in the policy scenario.

The final cost element is about the infrastructure cost. These contain the ERS and charging stations infrastructure in the policy scenario, and in the zero(+) alternative it contains the charging stations infrastructure. The cost for the ERS infrastructure does not change within the comparisons. The ERS infrastructure cost consist of the construction, maintenance, and connection to the power supply network. For the Western route the total ERS infrastructure cost, for the time span 2025-2054, is 284 million euros. The ERS infrastructure cost for the Middle route are 288 million euros. On the third route, the Eastern route, the total ERS infrastructure cost are 334 million euros. The infrastructure cost results are the differences between these ERS infrastructure cost and the charging stations infrastructure cost within the zero or zero+ alternative. The costs for charging station infrastructure depends on the number of battery trucks. The differences in the final infrastructure costs are the result of the fluctuations within the charging stations costs. For the zero+ alternative the charging station infrastructure cost are higher than in the zero alternative, this is due to the implementation of all charging stations in the year 2030 within the zero+ alternative, as explained in chapter 4.
The results show the NPV outcomes and B-C ratios between the policy scenario and the zero or zero+ alternative. The NPV is the results of the summations of the truck elements and the infrastructure element. In the next sections the results are explained and interpreted in more detail. The different components within the trucks elements and infrastructure element are visualized.

The results show the nine truck elements and infrastructure element. A positive delta value represents the savings made by the implementation of ERS infrastructure in the policy scenario. For example, in table 6.1, the Truck investment delta for the comparison between the policy scenario and zero alternative is 214 million euros. This means that the total costs for investments in new trucks is 214 million higher in the zero alternative compared to the policy scenario. The policy scenario has a positive impact.
For the Truck residual value, in the comparison between the policy scenario and the zero alternative, the value is -22 millions euros. This means that the total residual value for of all trucks within the zero alternative is higher compared to the policy scenario, since residual value is a earning. This means that in the policy scenario less is earned for re-selling the trucks.

Table 6.1: Results overview for the Western route

Comparison	Policy scenario compared with zero alternative	Policy scenario compared with zero alternative (opportunity charging)	Policy scenario compared with zero+ alternative
Truck investment delta (mln. euro)	214	310	258
Truck maintenance cost delta (mln. euro)	62	13	11
Truck residual value delta (mln. euro)	-22	-13	-11
Truck energy cost delta (mln. euro)	409	73	61
CO_2 cost delta (mln. euro)	530	115	96
NO_x cost delta (mln. euro)	63	0	0
PM_v cost delta (mln. euro)	3	0	0
Truck charge delta (mln. euro)	197	0	0
Truck tariff ERS (mln. euro)	-71	-71	-71
Infrastructure cost delta (mln. euro)	-278	-261	-262
Net Present Value (mln. euro)	1,080	166	151
Benefit-cost ratio	3.9	1.5	1.6

Table 6.2: Results overview for the Middle route

Comparison	Policy scenario compared with zero alternative	Policy scenario compared with zero alternative (opportunity charging)	Policy scenario compared with zero+ alternative
Truck investment delta (mln. euro)	231	333	278
Truck maintenance cost delta (mln. euro)	67	14	12
Truck residual value delta (mln. euro)	-27	-18	-15
Truck energy cost delta (mln. euro)	521	111	93
CO_2 cost delta (mln. euro)	653	142	118
NO_x cost delta (mln. euro)	77	0	0
PM_v cost delta (mln. euro)	4	0	0
Truck charge delta (mln. euro)	190	0	0
Truck tariff ERS (mln. euro)	-78	-78	-78
Infrastructure cost delta (mln. euro)	-281	-262	-191
Net Present Value (mln. euro)	1,358	242	219
Benefit-cost ratio	4.5	1.7	1.8

Table 6.3: Results overview for the Eastern route

Comparison	Policy scenario compared with zero alternative	Policy scenario compared with zero alternative (opportunity charging)	Policy scenario compared with zero+ alternative
Truck investment delta (mln. euro)	364	526	438
Truck maintenance cost delta (mln. euro)	105	23	19
Truck residual value delta (mln. euro)	-42	-28	-23
Truck energy cost delta (mln. euro)	857	162	135
CO_2 cost delta (mln. euro)	1,099	238	199
NO_x cost delta (mln. euro)	130	0	0
PM_v cost delta (mln. euro)	6	0	0
Truck charge delta (mln. euro)	300	0	0
Truck tariff ERS (mln. euro)	-143	-143	-143
Infrastructure cost delta (mln. euro)	-323	-294	-191
Net Present Value (mln. euro)	2,355	485	445
Benefit-cost ratio	5.6	2.0	2.3

6.2. Policy scenario compared to zero alternative

Uptake zero alternative: 0.16% (2023) - 3% (2030) - 14% (2040) - 46% (2054)
Uptake policy scenario (50% catenary trucks in 2054): 0.16% (2023) - 3% (2030) - 70% (2054)

The first comparison made in this research is the comparison between the policy scenario and the zero alternative. In this zero alternative no actions have been taken, therefore, the uptake of the electric trucks is according Fabius et al (2020), the uptake can be seen in chapter 4. The uptake included in the policy scenario is tested in different ways, three different uptakes are researched, of which one is shown in this section in table 6.4 and 6.5 (all results can be found in the Appendix C). The three uptakes tested are from 0,16% till 70% (electric trucks), the difference between the three uptakes is the final percentage of catenary trucks among the electric trucks. First the results are obtained for a 40% share of catenary trucks, followed up by a share of 50% and 60% catenary trucks (from the total number of trucks). In this chapter the results for a share of 50% of catenary trucks is discussed, this is assumed to be the most expected uptake if the ERS infrastructure is implemented. The ERS infrastructure construction is to be finished in 2030. In 2030 the percentage of electric trucks is 3%, it is expected that this percentage is growing besides the uptake of catenary trucks. Despite, the main uptake is among the catenary trucks, since these trucks will be cheaper (compared to battery trucks) and are able to charge dynamic.

From the results it can be seen that the NPV outcomes for the three route alternatives are positive (high value), this is the result of the differences in the uptake of electric trucks. Electric trucks (battery and catenary) are cheaper in use compared to diesel trucks, therefore big savings can be obtained when looking into the trucks cost. Table 6.5 show the savings according the different elements included in this research. In the zero alternative the number of battery trucks is limited, this results in a lower investment cost in the infrastructure for static charging stations. The ERS infrastructure cost in the policy scenario is not dependent on the number of catenary trucks using it, it is a fixed cost per route. The ERS infrastructure can be dependent on the number of catenary trucks, as explained in chapter 4, the number of sub-stations can depend on the number of catenary trucks using the ERS infrastructure. In this research it is assumed that, with a distance of 3.5 kilometers between the sub-stations, the total power demand needed by all catenary trucks can be fulfilled.

The infrastructure cost between the different routes does not differ much, the big difference between the NPV outcomes and B-C ratios is the result of the differences within the truck savings. The two main elements in this are the energy cost and the CO_2 emissions cost, both cost are dependent on the energy consumption. The energy cost is directly related to the energy consumption, the CO_2 emissions cost are based on the energy consumption.
It can be seen that the influence of the NO_x emissions and the PM_v emissions is relatively low, compared to the influence of the CO_2 emissions. In this research the PM_v emissions for battery trucks and catenary trucks have been set equal, in reality this will not be the case. Due to the catenary wear in the ERS infrastructure case. The tire wear on the other hand, is higher in case of the heavier battery trucks.

The differences between the scenario increase from the Western to the Eastern route, this is mainly caused by the difference in number of trucks. As described earlier, the main contributing elements are the energy cost and the CO_2 emissions cost. Both elements are directly related to the number of trucks. Looking for the results on the Eastern route, the energy savings are 857 million euros and the CO_2 emissions savings are 1,099 million euros, which is 1,956 million euros of savings of the total of 2,678 million savings within the truck elements.

In figure 5.5 the difference can be seen in the emissions of CO_2 for the policy scenario compared to the zero alternative over the years. It represents the total CO_2 emissions for total number of trucks in the scenarios. In 2030 the ERS infrastructure is completed and catenary trucks are in use, from this year on the CO_2 emissions are decreasing each year. In 2054 the total CO_2 emissions is lowered by 400 million kilograms. For the eastern route, the total CO_2 cost differ 1,238 million euros in the policy scenario compared to the zero alternative.

Table 6.4: Final results policy scenario compared to zero alternative (ERS 50% of the electric trucks)

	West	**Middle**	**East**
Net Present Value (mln. euro)	1,080	1,358	2,355
Benefit-cost ratio	3.9	4.5	5.6
Truck cost delta (mln. euro)	1,365	1,638	2,678
Infrastructure cost delta (mln. euro)	-278	-281	-323

Table 6.5: Final results policy scenario compared to zero alternative (ERS 50% of the electric trucks)

	West	**Middle**	**East**
Truck investment delta (mln. euro)	214	231	364
Truck maintenance cost delta (mln. euro)	62	67	105
Truck residual value delta (mln. euro)	-22	-27	-42
Truck energy cost delta (mln. euro)	409	521	857
CO_2 cost delta (mln. euro)	530	653	1,099
NO_x cost delta (mln. euro)	63	77	130
PM_v cost delta (mln. euro)	3	4	6
Truck charge delta (mln. euro)	197	190	300
Truck tariff ERS (mln. euro)	-71	-77	-143
Infrastructure cost delta (mln. euro)	-278	-281	-323

Opportunity charging comparison

Uptake zero alternative: 0.16% (2023) - 19% (2030) - 44% (2040) - 81% (2054)
Uptake policy scenario (60% catenary trucks): 0.16% (2023) - 19% (2030) - 44% (2040) - 81% (2054)

Secondly, a comparison is made between the policy scenario and the zero alternative in which opportunity charging is applied. In this comparison all trucks (in all scenarios) are able to charge its battery fully once over the day, this is called **opportunity charging**. As described in chapter 4, the uptakes are based on the uptake in the report of Tol et al (2022): a 25% increase in electric truck per 10 years. The only difference between the zero and zero+ alternative are the construction years of the charging stations, this results in only differences between the infrastructure cost. Both uptakes are equal and both scenarios only take into account battery trucks as electric trucks. Therefore, the comparison discussed in this chapter is the comparison between the policy scenario and the zero alternative. Within this comparison the number of catenary trucks in the policy scenario is 60% of the total number of trucks, resulting in 21% of battery trucks in the policy scenario in 2054. In Appendix C also the results are shown for 50% and 65% of catenary trucks within the policy scenario.

The NO_x emission cost, the PM_v emission cost, and the trucks charge cost differences for all three routes are 0, this can be explained by the input parameters of the research. In the research the variables for NO_x and PM_v have been set equal for catenary trucks and battery trucks. In reality there is probably a difference between the two type of trucks. The same counts for the truck charge cost. For diesel trucks the truck charge cost are 0.15 euro/km, an electric truck pays only 0.03 euro/km. Battery trucks and catenary trucks are both electric trucks and pay the same amount of truck charge per km. Since the uptake in both scenarios is taken equal, the summation of the truck charge for all trucks is equal in both scenarios. If an ERS infrastructure is to be implemented, differences in truck charge for battery trucks and catenary trucks could be implemented as well.

Table 6.6: Final results policy scenario compared to zero alternative with opportunity charging

	West	**Middle**	**East**
Net Present Value (mln. euro)	166	242	485
Benefit-cost ratio	1.5	1.7	2.0
Truck cost delta (mln. euro)	427	505	779
Infrastructure cost delta (mln. euro)	-261	-262	-294

Table 6.7: Final results policy scenario compared to zero alternative with opportunity charging

	West	**Middle**	**East**
Truck investment delta (mln. euro)	310	333	526
Truck maintenance cost delta (mln. euro)	13	14	23
Truck residual value delta (mln. euro)	-13	-18	-28
Truck energy cost delta (mln. euro)	73	111	162
CO_2 cost delta (mln. euro)	115	142	238
NO_x cost delta (mln. euro)	0	0	0
PM_v cost delta (mln. euro)	0	0	0
Truck charge delta (mln. euro)	0	0	0
Truck tariff ERS (mln. euro)	-71	-78	-143
Infrastructure cost delta (mln. euro)	-261	-262	-294

6.3. Policy scenario compared to zero+ alternative

Uptake zero+ alternative: 0.16% (2023) - 3% (2030) - 70% (2054)
Uptake policy scenario (50% catenary trucks): 0.16% (2023) - 3% (2030) - 70% (2054)

Besides the comparison between the policy scenario and the zero scenario, the comparison between the policy scenario and the zero+ alternative is made. Here the main difference is that all charging stations are constructed in 2030.
Table 6.8 show that the NPV is the highest on the Eastern route, this difference is caused mainly by the differences in truck savings. The differences between the infrastructure cost is only 10 million between the different routes (which is the result of the different ERS infrastructure lengths), the differences in truck savings are around 200 million euros between the Western/Middle route and the Eastern route.

Comparing the results with the results of policy scenario - zero alternative comparison, it can be seen that the total difference in CO_2 emission cost is around 5 times lower. This can be substantiated by the influences of the WTW emissions for diesel trucks, battery trucks and catenary trucks. As described in chapter 5 (figure 5.3), the energy needed to produce 100 kWh for the wheels of battery trucks is 144 kWh, for catenary trucks this is 130 kWh. This means that there is a difference between the CO_2 emissions of the two types of electric trucks. In the first comparison most trucks are still driving on the Industrial Combustion Engine, which needs 263 kWh to produce 100 kWh at the wheels. This results in a higher total kilograms of CO_2 emissions and finally in higher CO_2 emission cost.

Table 6.8: Final results policy scenario compared to zero+ alternative (70%)

	West	**Middle**	**East**
Net Present Value (mln. euro)	151	219	445
Benefit-cost ratio	1.6	1.8	2.3
Truck cost delta (mln. euro)	334	408	625
Infrastructure cost delta (mln. euro	-194	-191	-180

Table 6.9: Final results policy scenario compared to zero+ alternative (70%)

	West	**Middle**	**East**
Truck investment delta (mln. euro)	258	278	438
Truck maintenance cost delta (mln. euro)	11	12	19
Truck residual value delta (mln. euro)	-11	-15	-23
Truck energy cost delta (mln. euro)	61	93	135
CO_2 cost delta (mln. euro)	96	118	199
NO_x cost delta (mln. euro)	0	0	0
PM_v cost delta (mln. euro)	0	0	0
Truck charge delta (mln. euro)	0	0	0
Truck tariff ERS (mln. euro)	-71	-78	-143
Infrastructure cost delta (mln. euro)	-194	-191	-180

6.4. Sensitivity analysis

In this chapter the sensitivity analysis is described according the different input variables used in this research. The main contributing input parameters are shown for the three different routes, since not all input parameters do influence the NPV relevantly. In Appendix D the most influencing parameters are shown in table form. The sensitivity analysis is tested by increasing and decreasing the input parameters one by one with +10% and -10%. There are some exceptions, for the input parameters 'Daily trips', 'ERS distance', 'CO_2 emission cost, 'NO_x emissions cost', 'PM_v emissions cost', 'Infrastructure lifetime', and 'Chargers per station' other lower and upper values have been used to test its sensitivity. These other values can be seen in table 6.10. For the ERS distance on the three alternative routes, only the lower limit is tested on sensitivity. The base ERS distance is the maximum distance of ERS that is possible on the routes, therefore the upper limit is left blank in this analysis.

Table 6.10: Sensitivity analysis truck elements not -10% or +10%

Truck element	**Lower**	**Base**	**Upper**
Daily trips	3	4	5
ERS distance West	54.9	61	-
ERS distance Middle	55.8	62	-
ERS distance East	64.8	72	-
CO_2 emission cost	0.05	0.13	0.16
NO_x emissions cost	18.3	29.9	44.1
PM_v emission cost	41.4	69.3	97.9
Lifetime sub-station, safety barriers, transformer	20	25	27
Lifetime catenary, power electronics	8	12	15
Chargers per station	7	8	9

For all three routes, the sensitivity analysis between the policy scenario and sensitivity analysis only gave one outstanding percentage, namely the lower cost for the CO_2 emissions. Within the zero alternative (uptake electric trucks: 46% in 2054), most trucks are still driving with the Industrial Combustion Engine. The results for this comparison show the high NPVs, mostly caused by the energy cost and the CO_2 emissions. Consequently the total kilograms of CO_2 emissions is higher than the total kilograms of CO_2 emissions within the policy scenario. The decrease in CO_2 emission cost per kilogram affect the NPV outcome for all three routes by 30%.

The sensitivity analysis for the other two comparisons tested in this research show big influences of input parameters, which differ per route alternative. Most input parameters depend on the number of trucks, the length of the route and the ERS infrastructure length. In the next subsections these input parameters are discussed per route alternative. The uptakes used within the NPV calculation and the sensitivity analysis are as follows:

Opportunity charging: Policy scenario: 0.16% - 81% (60% catenary trucks); Zero alternative: 0.16% - 81%
Zero+ alternative: Policy scenario 0.16% - 70% (50% catenary trucks); Zero + alternative: 0.16% - 70%

6.4.1. Western route and Middle route alternatives

The sensitivity analysis of the Western route is visualized in figures 6.2 and 6.3. For the Middle route the results of the sensitivity analysis can be seen in figures 6.4 and 6.5. These are the eight parameters that have an influence of 25% or higher on the resulting NPV compared to the base NPV result, the other influences of the parameters are not reflected on.

Mainly the NPV is based on the energy savings and the CO_2 emissions savings, see table 6.5. Therefore, the sensitivity analysis is mostly affected by the adjustments made to the energy consumption, energy cost, and CO_2 emissions cost. The biggest influencing input parameter on these routes is the energy consumption of the battery trucks. The battery truck energy consumption is included in different ways within the calculations of the NPV. In the results it can be seen that the energy consumption of battery trucks is taken into account in the energy savings. Battery truck energy consumption is calculation by the energy cost and included. Besides the direct calculation of the energy cost, via the energy consumption, the energy consumption also influence the results on CO_2 emissions cost. As described in section 5.2 (formula 5.11), the total kg of CO_2 emissions is calculated according the WTW energy consumption of the truck. This means that the influence of the energy consumption is included in the energy savings and in the CO_2 emissions savings. Equally, this counts for the high sensitivity result for the energy consumption of the catenary trucks.
Secondly, the electricity cost for ERS and charging stations affect the NPV result when adjusting the electricity prices. The sensitivity value for the two electricity prices is equal.
The difference in CO_2 emission cost is the result of the differences in type of electric trucks. The uptake for the policy scenario is similar to the uptakes in the zero+ alternative and the opportunity charging alternative. The difference between CO_2 emissions of battery trucks and the CO_2 emissions of catenary trucks are the base for the change in NPV while adjusting the CO_2 emission cost
For the catenary lines it can be seen that the NPV changes are bigger for the shorter lifetime compared to the higher lifetime. This can be explained by the lifetimes chosen, 8 en 15 years. By rebuilding the catenary lines each 8 years, the cost for the infrastructure (over the 30 years) goes up. The increase in infrastructure cost is also accounted for in the tariff ERS price. The combination of the influence of the lifetime of the catenary lines result in the big difference between the NPV results.

The ERS distance parameters have an impact on multiple calculations. It affects the total ERS infrastructure cost, which affects the tariff ERS parameter. Besides, the ERS length influences the energy use of the catenary trucks. With a shorter ERS infrastructure on the road, the truck is using more electricity out of its battery. This results in more energy consumption for the catenary trucks.

The combination of affected calculation result in a higher NPV for the Western routes and Middle routes. The differences in NPV results are higher for the Western route compared to the Middle route, this is caused by the lower number of trucks using the ERS infrastructure. The lower the number of catenary trucks using the ERS infrastructure, the higher the ERS tariff is for the catenary trucks making use of the infrastructure.

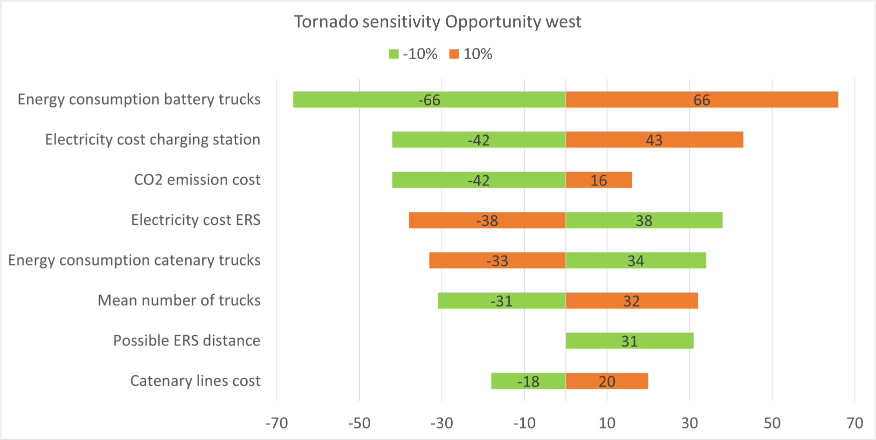

Figure 6.2: Sensitivity analysis results: policy scenario - zero alternative (opportunity charging)

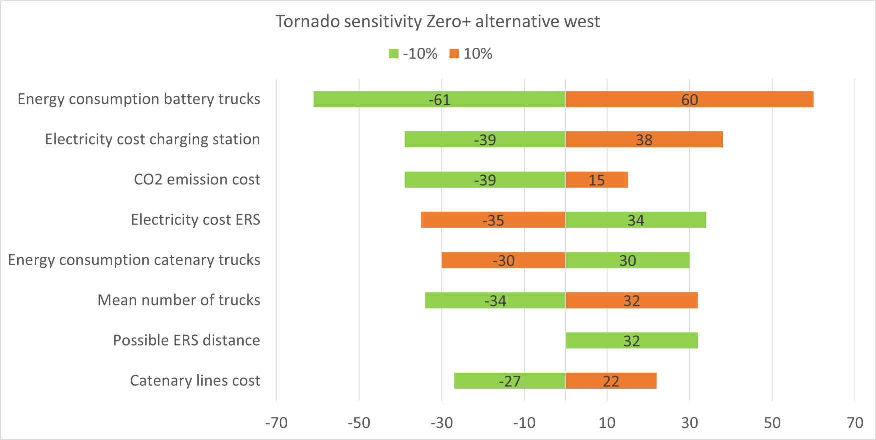

Figure 6.3: Sensitivity analysis results: policy scenario - zero+ alternative

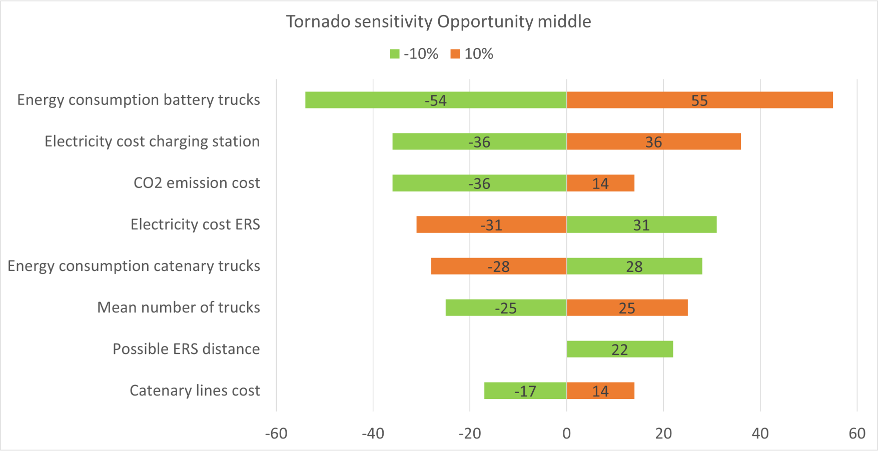

Figure 6.4: Sensitivity analysis results: policy scenario - zero alternative (opportunity charging)

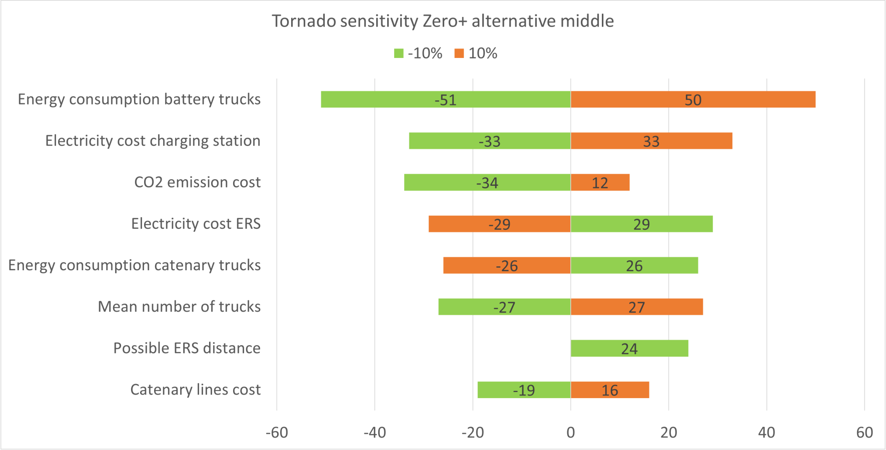

Figure 6.5: Sensitivity analysis results: policy scenario - zero+ alternative

6.4.2. Eastern route alternative

Figures 6.6 and 8.21 show the results of the sensitivity analysis for the Eastern routes, comparing the policy scenario with the zero+ alternative and the opportunity charging alternative. From these two figures, it is clear that the input parameters are less affected in the Eastern route than within the Western and Middle routes. The NPV changes is less than 25% for the parameters 'mean trucks', 'ERS distance', and 'catenary lines'. The change in NPV for adjusting ERS electricity cost on the Eastern route is comparable with the NPV change in the Western and Middle routes.

Within all the sensitivity analysis of the three route alternatives, the NPV results is never changed by more than -100%, this means that all NPV results are still positive.

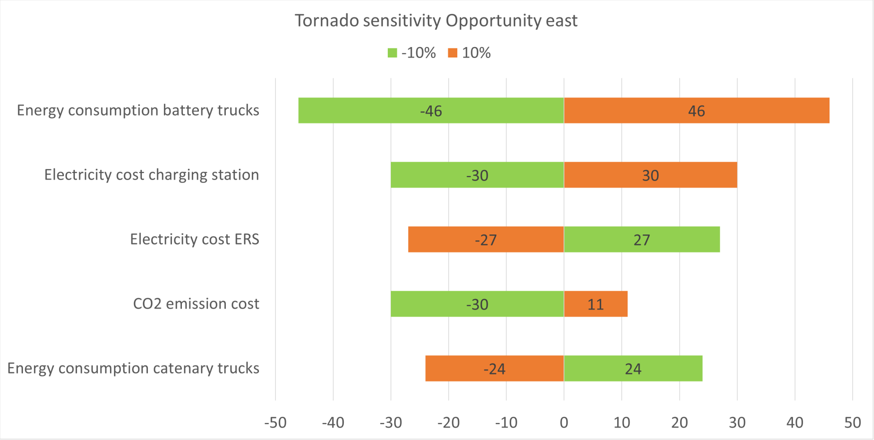

Figure 6.6: Sensitivity analysis results: policy scenario - zero alternative (opportunity charging)

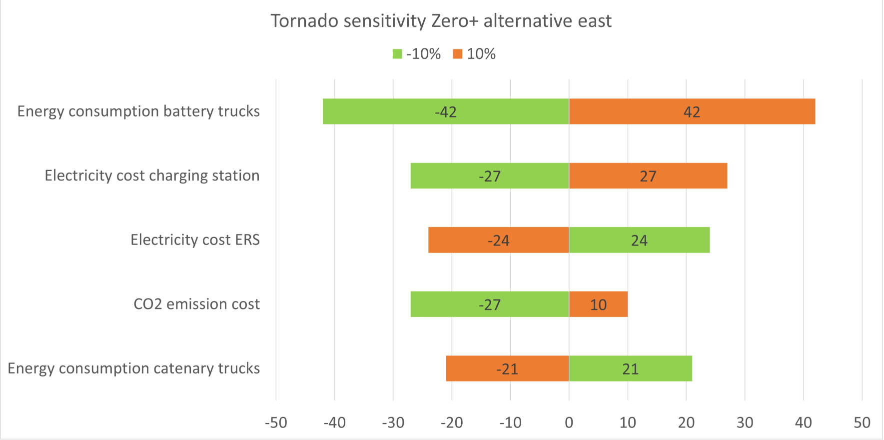

Figure 6.7: Sensitivity analysis results: policy scenario - zero+ alternative

6.4.3. Most influencing parameters studied in more depth

In this section the five most influencing variables are explained in more depth according the comparison between the policy scenario and the zero alternative. The uptake of electric trucks taken into account in this explanation is with opportunity charging. In figure 8.15 the NPV outcomes are shown for the different input of the most influencing variable: the energy consumption of battery trucks. The normal energy consumption of battery trucks is 1.44 kWh/km. It can be seen that for an energy consumption of around 1.04 kWh/km, the NPV outcomes for all three alternative routes are equal (around -130 million euros). The different routes cross the 0 NPV limit in at different energy consumptions. For the Eastern route this is the lowest energy consumption (compared to the Middle and Eastern routes), namely at 1.13 kWh/km. This is related to the longer distance of the Eastern route in combination with the number of trucks transporting on the Eastern route.
The relation between the energy consumption of battery trucks is linear to the NPV outcomes of the SCBA calculations. This is the fact for all variables used in this study. In Appendix E the figures are shown for the variables: Energy consumption battery trucks, Energy consumption catenary trucks, Electricity cost charging station, Electricity cost ERS and CO_2 emissions cost.

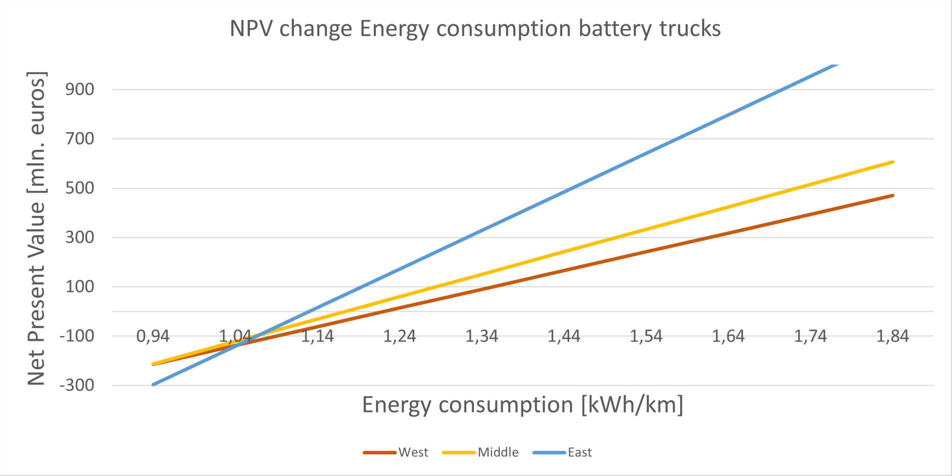

Figure 6.8: Sensitivity analysis NPV results for the direct effect: Energy BT

For the CO_2 emission cost the lower limit is 0.05 Euro/kg and the upper limit is 0.16 Euro/kg, according de Bruyn et al (2023). From figure 6.2 the CO_2 emissions cost showed a change in NPV of -42% at a 0.05 Euro/kg cost for CO_2 emissions, from which it can be concluded that the CO_2 emission cost has a big influence in the NPV outcome. Looking into the direct effect in more depth, it can be seen that NPV outcome has a linear relation with the CO_2 cost (figure 6.9). The base price for CO_2, according de Bruyn et al (2023), is 0.13 Euro/kg, this causes the big difference in NPV change according the lower limit for CO_2 emission cost. Figure 6.9 shows that the difference in NPV changes is not affected much by changing the CO_2 emission cost. This concludes that the CO_2 emission cost affects the outcome of the NPV significantly, when addressing the lower limit, but is not of great influence when adjusting the variable in between the lower limit and base value.

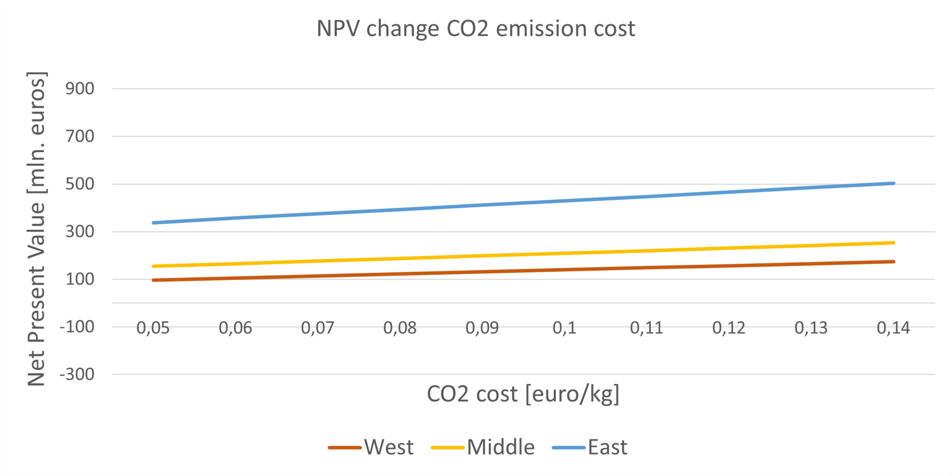

Figure 6.9: Sensitivity analysis NPV results for the direct effect: CO_2 cost

The figures for the five most influencing variables of the comparison between the policy scenario and the zero+ alternative do have the same shapes as the figures for the comparison between the policy scenario and zero alternative (with opportunity charging). These figures are also added in Appendix E.

To conclude, the four variables (Energy consumption battery trucks, Energy consumption catenary trucks, Electricity cost charging station and Electricity cost ERS) affect the NPV outcome significantly when adjusting the variables. The NPV calculation has a linear relation with all directs effects and input parameters involved in the calculations. The CO_2 emission cost on the other hand, do affect the NPV value significantly if only taken into account the adjustment from the base value towards the lower limit. Looking at the variable between the base value (0.13 Euro/kg) and lower limit (0.05 Euro/kg), the CO_2 emission cost variable influences the NPV outcomes less than expected.

6.4.4. Combination of direct effects and input parameters

The sensitivity analysis is tested in more depth by adjusting the most influencing variables at the same time and see what happens. From the previous sections, it can be assumed that two variables which affect the NPV outcome in a positive way, the combined NPV outcome will be double as positive. In this section the results are shown for the combined variables on the Western route. This route is chosen since the changes in NPV outcome are the highest. The NPV changes for the Middle route and Eastern route have been added in Appendix F. Moreover, from the previous sections, it became clear that there is a linear relation between changes in variables and the NPV outcome. Within the combination of changing variables, the NPV outcome becomes non-linear in some cases. This is caused by the relation between the variables within the SCBA calculations. Looking at the first comparison in figures 6.10 and 6.11, the energy consumption of battery trucks and electricity cost at charging stations have both been decreased and increased by 10%. The cost for electricity per kilometer will therefore be:

$$-10\% \text{ value} = (0.19 \text{ Euro/kWh} * 0.9) * (1.44 \text{ kWh/km} * 0.9) = 0.22 \text{ Euro/km} \tag{6.1}$$

$$+10\% \text{ value} = (0.19 \text{ Euro/kWh} * 1.1) * (1.44 \text{ kWh/km} * 1.1) = 0.33 \text{ Euro/km} \tag{6.2}$$

The -10% value for the cost per kilometer differ more from the base cost (0.274 Euro/km) compared to the +10% value. The -10% value differs 0.052 Euro/km and the +10% value differs 0.058 Euro/km, this results in a non-linear outcome for the sensitivity analysis.

The non-linearity within the Mean number of trucks and Catenary lines cost is caused by the different lifetime taken into account for the catenary lines, as described at the beginning of this section. This is caused by the multiplication of two factors (factor times factor).

As expected, the combination of changes within the variables result in bigger changes in the NPV outcomes. Figures 6.2 and 6.3 already show the NPV outcome changes for the -10% and +10% changes. If we look at the -10%, it is clear that most variables result in a lower NPV by the adjustment, and vice versa for +10%. With a combination of two variables, which do result in a lower NPV when adjusting by -10%, the NPV is even more negative, but not the summation of the two. This is caused by the effect between the variables, as explained above, within the calculation of the SCBA. The combination of the Energy consumption battery trucks and Electricity cost charging station is expected to be -100% (-61 + -39), but due to the formulas the outcome is -95% (from figures 6.3 and 6.11. This also happens within other comparisons, but these comparison are almost nil.

Looking at the outcome for the most influencing variables combined, the -10% value is -87% and the +10% value is 98%. The summation of the -10% values within the NPV changes from figure 6.3, result in a -104% change according the green bars summed. Comparing this to the -87% NPV change outcome within figure 6.11, this is a difference of 17%. This difference is due to the mutual effects within the SCBA calculations, as explained for theEnergy consumption battery trucks and Electricity cost charging station combination.

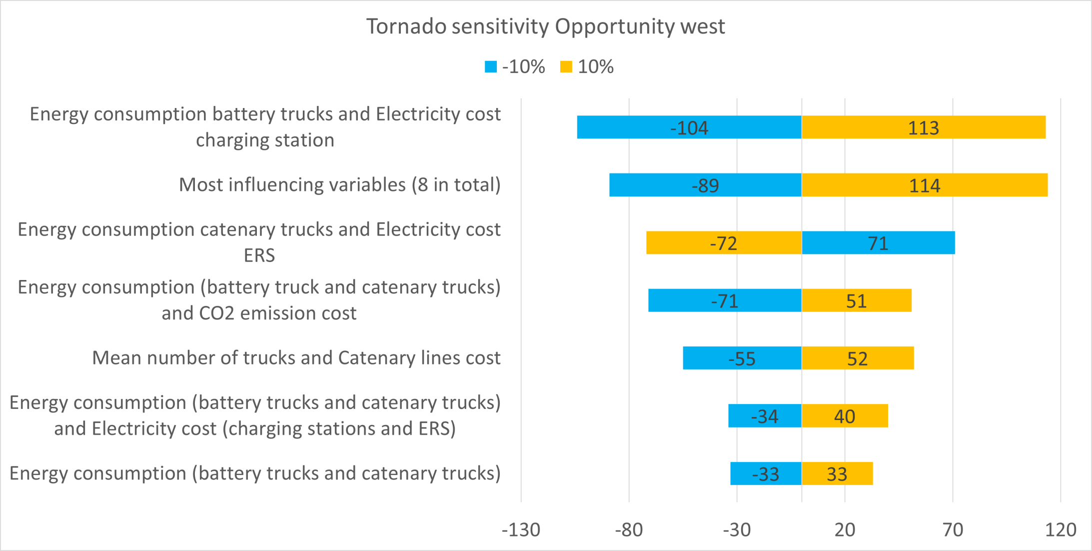

Figure 6.10: Sensitivity analysis NPV results variables combined: policy scenario - zero alternative with opportunity charging

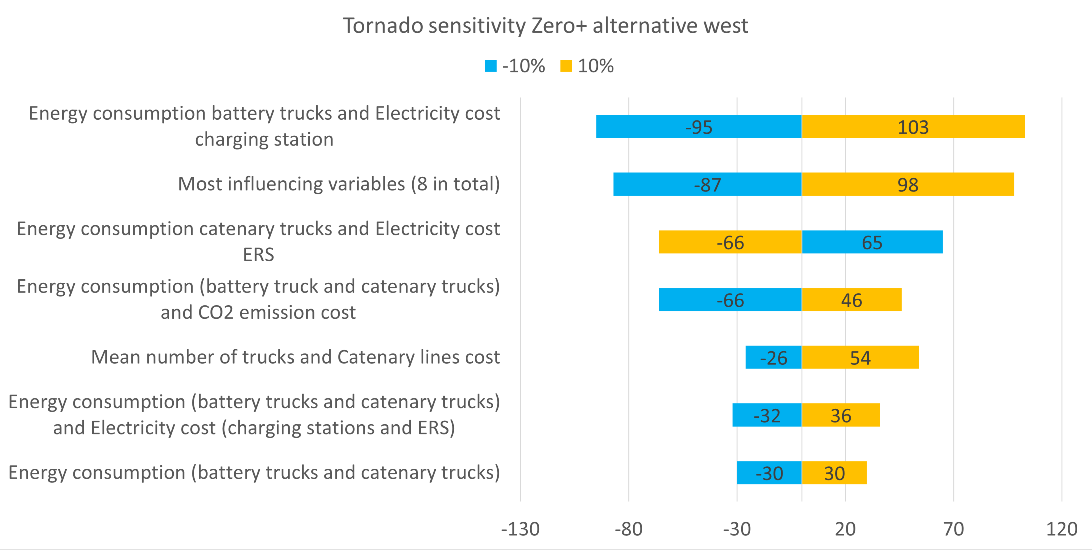

Figure 6.11: Sensitivity analysis NPV results variables combined: policy scenario - zero+ alternative

7

Discussion

Based on the policy scenario and the sensitivity analysis executed in chapter 6, the limitations of the research are discussed in section 7.1. In section 7.2 as short discussion is given on the data references. Finally, in section 7.3 some other interesting discussion points are mentioned.

7.1. Discussion on research execution

Field trip and google maps

The first step of the research was the visualization of the three alternative routes between the port of Rotterdam and the port of Antwerp. This is performed by literature review towards the implementation of ERS infrastructure, discussion with experts in the ERS field, and a visual inspection via a field trip and google maps. The combination of the results in the assumption on the length of the ERS infrastructure on the routes. Other assumptions of the ERS length result in different result within the NPVs and B-C ratios.
Moreover, the ERS lengths used in the calculations of the ERS infrastructure costs are the maximum assumed lengths. If the route between the port of Rotterdam and the port of Antwerp is only used by shuttle transport between the two ports, the ERS length on the three alternative routes can be optimized. In this research the minimum needed ERS length is not calculated. To calculate the optimal ERS length, for shuttle trucks only, other input parameters as energy losses on the catenary lines have to be taken into account. In this research the ERS infrastructure on the three routes is seen as the start of an European network. Therefore the maximum assumed ERS length are used in the calculations.

Scenarios

In the research the zero alternative is described as the alternative where the uptake of electric trucks is happening, in combination with diesel trucks. In reality other fuel types will play a role in the uptake as well. Fabius et al (2020) already included electric trucks and hydrogen trucks, for simplicity the uptake in this research was assumed to only included battery trucks as electric trucks. Another assumption was made on the non electric trucks. All these trucks have been included as the standard diesel Industrial Combustion Engine trucks. Besides diesel, battery and catenary trucks, there are more fuel technique options that can be included in the research: Fuel Cell Electric Vehicle (FCEV), e-fuels, Biofuel, Natural gas or Ammonia. This research did not take into account these fuel technique types in the calculations, but these types can be expected in the coming years.
Besides the different fuel techniques, the uptake for electric trucks is assumed to be linear in all comparisons between the policy scenario and the zero(+) alternative. In reality the uptake of electric trucks will probably not be linear. The uptake is dependent on multiple factors. For example the scarcity of raw materials for the construction of battery/catenary trucks. The implementation of subsidies by governmental entities can result in a quicker uptake in the beginning years (as explained in the report of Tol et al (2022)). Moreover, product prices could increase due to worldwide disasters, like wars or natural disasters.
Assumed is that the power supply network of the Netherlands can fulfill the power demand for all catenary and battery trucks. It is not obvious that the power supply network can fulfill the needs for all trucks the charge (static or dynamic), especially in crowded areas. If the power supply network can be extended in future years is yet unknown.

Subsidies have not been taken into account in this research, since it is not stated that the government should fulfill the role for investor for the ERS infrastructure or backbone for the investment in electric trucks. Now only linear uptakes have been taken into account, but with the use of these subsidies for the infrastructure and trucks cost, it could be more attractive to transport companies to invest. This can result in other uptakes of electric trucks, as described in Tol et al (2022), which includes the 'AanZET' and 'Terugsluis' subsidies. The impact on the uptake is interesting, but also difficult to estimate.

SCBA: Input parameters and calculations

For the calculations of the energy prices, energy consumptions and emissions fixed values are used. Costs for diesel and electricity for example are changing every day. To create a more realistic outcome, a forecast should be made on these input parameters. Despite a forecast, it is still guessing what the value will be in 10 or 20 years. Moreover, the impact of wars, natural disasters and other worldwide happenings, cannot be included in a forecast, but will have a mega impact on the prices.

Besides the length of the ERS on the three routes, as explained earlier, also the distance between the sub-stations can be optimized. This research only takes into account the distance of 3.5 kilometers in between the sub-stations. With a distance of 3.5 kilometers, the ERS infrastructure is assumed able to fulfill the needs of all connected trucks taken into account in this research. With a more increasing number of trucks using the infrastructure, if a European network will be implemented, the need for more sub-stations in between is needed. Besides the need for more sub-stations, the increase in number of users will result in a faster wear of the catenary lines. As described in chapter 6, the lifetime reduction of the catenary lines has a big impact on the outcome of the NPV results.

For the comparisons between the policy scenario and the zero(+) alternatives with an equal uptake, the NPV results for NO_x emissions, PM_v emissions and truck charge are zero. This is due to the equal number of emissions and truck charge cost for battery and catenary trucks. Within the comparison between the policy scenario and the zero alternative (unequal uptake) the three parameters give a delta between the scenarios. In reality the PM_v values will differ for catenary and battery trucks. Battery trucks weigh more, which results in more tire wear. Catenary trucks on the other hand cause more PM_v emissions due to the catenary wear and the pantograph wear.

Finally, the non-monetized direct effects and input parameters can have a big impact towards the outcome of the real feasibility of the ERS infrastructure. These non-monetized variables are taken into account in the conclusion, but should be researched in depth. For example the influence of the implementation on other traffic on the highways. Due to the implementation of the ERS infrastructure, a route shift among trucks can arise. If the highway is already extremely busy, the arise of more congestion is inevitable. Also the truck movements are probably changing due to the ERS infrastructure.

Final decision on route supported with a MCA or other comparison between the routes

The main goal of this research was to show the feasibility of an ERS infrastructure between two freight handling locations. Between the two freight handling points, three alternative routes have been included. From the NPV results, a difference and first conclusion, can be outlined on the best alternative route between the port of Rotterdam and port of Antwerp. A conclusion on which route to take was not the main objective of the research, but an interesting extension towards the research. To finally choose between the three alternative routes, more research is needed. With the outcome of the SCBA a Multi-Criteria Analysis (MCA) can for example be performed, or another decision making method (Niek Mouter 2021). A MCA (Aruldoss, Lakshmi, and Prasanna Venkatesan 2013) will be an interesting research method for the decision between the routes because more effects arise, which cannot be monetized, with the ERS infrastructure implementation. As shown in chapter 5, effects as congestion on the routes and travel time savings (due to dynamic charging instead of static charging) can play a vital role within the decision making. Furthermore, different input parameters can be taken into account to distinguish between the three route options. These parameters can be: surroundings of the highway, surrounding distribution centers and connection of these distribution centers to the highway, surrounding big cities, number of special constructions and connection to further highway network. The decision making on which route to choose is dependent on all these parameters that have not been taken into account in this research. The main goal was to test the feasibility of the ERS infrastructure, not the choice between the three route alternatives.

Research gap

The identified gap in the existing literature relates to the absence of a Social Cost Benefit Analysis (SCBA) regarding the implementation of an Electric Road System (ERS) infrastructure between two freight handling points. This study specifically conducts an SCBA focused on the case study involving the port of Rotterdam and the port of Antwerp, thereby addressing this research gap.

One of the most intriguing aspects of conducting an SCBA between two ports is the calculation involving the quantity of trucks operating between the two ports ('shuttle' trucks). However, in this research, an assumption is made that catenary trucks are shuttling between the ports due to insufficient data regarding the origins and destinations of heavy duty trucks. It should be noted that the actual number of shuttle trucks might deviate from the assumption made in this research. Therefore, the reliability of the research can be increased significantly with data available on the origins and destinations of trucks.

7.2. Data references

Different literature studies combined from different years

Multiple papers and assumptions have been used in the calculations of the SCBA. These papers are published in different years. Moreover, the researches have been performed in different countries. Each country has its own values for the involved parameters. For example diesel price, each country has it own diesel price which fluctuates over the years.

7.3. Other discussion points

The case study of this research originally takes place in two countries, the Netherlands and Belgium. Therefore different input values are needed for the infrastructure and truck cost within the different countries. To simplify the calculations, only the Dutch input parameters have been used. In order to create a more exact representation, the highways should be split into the two countries with its own values (truck charge, construction cost) and policies. Besides the difficulty of two different countries, it is hard to combine the right costs for all included components. The cost parameters used in this research come from multiple reports, also from foreign countries. The prices used in foreign countries do not have to be the same in the Netherlands or Belgium.

Besides the change in electricity cost over the years, the costs for electricity can differ for public charging locations and private charging locations. For the ERS construction the electricity will probably be public charging. but in case of charging stations this can differ. Besides, if a company has its own charging station, it can earn money by letting other transport companies charge their trucks by their chargers.

Also the location of the charging stations is of importance. In this research only the number of charging stations is taken into account. The location along the route is important for the calculation, these stations should be located at logic places to fulfill the need for electricity. If the location is known, the costs that come with it will come into play. If the charging stations is located besides the highway, the ground for the charging station has to be bought or rented. This is not only the case for charging stations, within the ERS infrastructure this would be a cost factor as well. This has been left out of the research, since the comparison between the ERS infrastructure and charging stations is made. The ground costs would have settled against each other in the comparison.

8

Conclusion and recommendations

In this chapter, the overall conclusion of this research is explained by answering the sub-question based on the performed research in the previous chapters. The result will be an answer towards the main research question. Finally, recommendations will be given for further research towards the feasibility of an ERS infrastructure between two freight handling points.

8.1. Conclusion

First, answer will be provided towards the five sub-questions from this research. Finally, the main research question will be answered.

What are the highway characteristics and limitations that have to be taken into account for the implementation of an ERS infrastructure?

Along highways, it is generally quite feasible to install ERS (Electric Road System) infrastructure. The only consideration lies in ensuring that there is adequate space directly alongside the highway for the construction of the poles, and slightly farther away from the highway (depending on the distances in between) for accommodating the sub-stations. In addition to the straight segments on highways, there are also special constructions. Special constructions are tunnels, bridges, and level crossings that pose challenges for installing ERS infrastructure, as detailed in chapter 3. Near these special structures, according to experts, feasibility remains untested and uncertain. Consequently, these sections have been excluded from consideration in this study.

Regarding two other specific structures, namely overpasses and service areas, it is possible to construct ERS infrastructure. However, achieving this requires a reinforced construction to ensure success. In table 8.1, the list of highway characteristics with the difficulty of implementing an ERS infrastructure is added.

Table 8.1: Difficulty implementation ERS infrastructure for special highway constructions
(++: possible, +: possible but extra conditions, +-: possible but extremely difficult, - impossible for now)

Highway element	**Difficulty implementation ERS infrastructure**
On- and off-ramps	++
Weaving section	++
Lane endings	++
Tunnels	-
Bridges	-
Level crossings	+-
Overpasses	+
Service areas and other road-side provisions	+
Safety barriers	++

Which social effects arise by the implementation of an ERS infrastructure?

The social effects that arise from the ERS infrastructure policy measure are divided into two sub-groups: the direct effects and the indirect effects. The direct effects are the effects that are directly related to the policy measure that is taken in the policy scenario. These effects consists of the social costs and benefits that occur towards the market the measures are taken into. To incorporate the direct effects into the calculations of this research, the direct effects have been monetized. The monetized effects fall into two distinct sub-categories: infrastructure costs and truck costs. Infrastructure costs exist of the ERS infrastructure and charging stations infrastructure. As the policy scenario includes an uptake of catenary trucks, this inevitably impacts the presence of battery trucks. Consequently, with fewer battery trucks in in the policy scenario, there is a reduced need for additional charging stations in the foreseeable future, this is a direct outcome of the policy measure. The infrastructure costs specifically involve:

- ERS infrastructure costs (energy feeding point, connection to the power network construction, substations, poles, catenary, safety barriers and other project costs)
- Charging stations infrastructure costs (energy feeding point, connection to the power network construction, power electronics, transformer and other project costs)
- Maintenance costs (ERS infrastructure, safety barriers and charging stations infrastructure)
- Connection to the power network yearly costs (standing charge, contracted power and maximum power)

Furthermore, the direct effects encompass truck costs. These costs entail expenses related to purchase, usage, and consumption. The monetized direct effects within the truck costs are: Purchase costs, battery costs (battery truck and catenary truck, pantograph cost (catenary truck), maintenance costs, residual value, energy consumption and energy cost, truck charge and Eurovignet costs, and CO_2, NO_x and PM_v emissions cost.

In addition to the monetized direct effects, a set of non-monetized direct effects has been summarized in chapter 5. Because these are not monetized, these direct effects did not affect the outcomes of the NPV results and B-C ratios. However, these direct effects are still important in the conclusion of the feasibility of the policy measure. The six non-monetized direct effects included are: special construction adjustments, travel time savings, area savings alongside highways, safety, highway view and congestion and route shift of trucks.

What other input parameters, besides the social effects, are needed to calculate the feasibility of an ERS infrastructure?

For the calculations within the SCBA, not only the direct effects are essential. Input parameters are necessary which are not directly the result of the policy measure, but cannot be omitted. These input parameters are related to the characteristics of the three alternative routes (West, Middle and East) and the transportation of the trucks. The following input parameters have been applied in the calculations of the NPV results and B-C ratios:

- **Distance of the route**: the distance of the route is needed for the calculation of the energy savings, emissions savings and the truck charge savings.
- **Possibility distance to build the ERS infrastructure**: the possible ERS distance on each route assist the calculations for the infrastructure costs, energy savings and tariff ERS costs.
- **Mean number of trucks per route**: the mean number of trucks is necessary within all truck related calculations for the final NPV results. The mean number of trucks is split into the diesel trucks, battery trucks and catenary trucks. The final calculations contain the results for all trucks in the scenario.
- **Mean number of truck growth per year**: is calculated of the mean number of truck per route to forecast the mean number of trucks in the next year
- **Trips per day per truck**: a truck is transporting freight between the two port a number of trips per day. With the trips per day per truck, the total distance travelled per truck (and finally for all trucks) per day is calculated.

- **Transporting days per year per truck**: for the yearly calculations the trips per day per trucks is multiplied by the number of days per year the truck is transport freight. The multiplication of the route distance by the trips per day by the days per year result in the total distance travelled per year.
- **Uptake of electric trucks (battery and catenary)**: the uptake of electric trucks is used as input for the policy scenario and the zero alternative. The uptake is, same as the mean number of trucks, necessary within all truck related calculations.

In addition to the previously mentioned essential input parameters, within the calculation of the infrastructure costs and the truck cost other input parameters cannot be omitted. The parameters used within these calculations are:

- Distance between sub-stations (ERS infrastructure)
- Truck per charger per day (charging station infrastructure)
- Chargers per charging station (charging station infrastructure)
- Percentage connected to ERS infrastructure (catenary trucks)

What is the Net Present Value according the policy scenario?

For the calculations in the SCBA, the highway characteristics and limitations, the direct effects arising from the policy measure, and the other input parameters (obtained with the first three sub-questions) have been used. In combination with the formulas, as described in chapter 5, the directs effects and input parameters have been used for the NPV calculations.
The results show that for all comparisons between the policy scenario and the zero(+) alternatives (including different uptakes of electric trucks), the NPV results are positive. In all comparisons the infrastructure costs for the policy scenario result in a negative NPV. The trucks costs on the other hand deliver a positive NPV for all comparisons.
The Eastern route comes out as the most positive NPV for all comparisons. This is caused by the higher mean number trucks transporting on this route. Due to the higher mean number of trucks, more diesel trucks are replaced yearly by battery or catenary trucks.

Which uncertainties, within the direct effects and the input parameters, will lead to big changes in the Net-Present Value calculation?

In the sensitivity analysis, all direct effects and input parameters were tested on the sensitivity. Most variables were tested using the lower (-10%) and upper (+10%) limits. For variables with a lifetime aspect and some others, different lower and upper limits were used to assess sensitivity. The most substantial differences in NPV results come from the adjustments in the Energy consumption of battery trucks. Other variables that exhibited an impact of 25% or more included the Electricity cost charging station, Electricity cost ERS, CO_2 emissions cost, and the energy consumption of catenary trucks. These five variables significantly influenced the NPV outcomes for all three route alternatives. Additionally, three variables within the Western route and Middle route affected the NPV outcomes by more than 25%: catenary, ERS distance, and mean number of trucks.
The five variables are studied in more depth as described in chapter 6, it is shown that all variables have a linear outcome with the NPV results. The variation in NPV results is significant for four variables. For the CO_2 emissions cost it can be seen that the variation in NPV result is less steep compared to the other four variables when adjusting the cost/kg CO_2.

What is the socio-economic feasibility of the implementation of an Electric Road System (ERS), the overhead catenary line system, between two freight handling points?

As outlined in the introduction, the initial setup for establishing an European ERS network involves a short route at the start between two freight handling locations. Because the route is between two freight handling locations, the high utilization of the ERS infrastructure can be guaranteed. This study explores the feasibility of ERS infrastructure between the ports of Rotterdam and Antwerp. The three alternative routes were mapped and assessed for potential ERS implementation. Additionally, significant variables for testing the feasibility were gathered from previous studies. As explored in preceding chapters, numerous direct effects and input parameters can significantly influence the outcomes.

The NPV results and B-C ratios across all examined comparisons yield positive NPV and a B-C ratio exceeding 1. These results suggest that the implementation of an ERS infrastructure between the ports of Rotterdam and Antwerp, across all three route alternatives, is feasible. However, it's essential to note that this conclusion relies on the chosen and assumed variables. As discussed, many variables did exhibit considerable deviation in the sensitivity analysis, casting doubt on the results. Despite the doubts arising from the sensitivity analysis, the NPV is changed by more than -100% only for the combination of the -10% values for the variables: 'Energy consumption battery trucks' and 'Electricity cost charging station'. This result of the sensitivity analysis shows that the NPV becomes negative only for this combination of variables.
Moreover, fixed values were utilized for most variables throughout the entire time span, whereas these fixed variables would significantly fluctuate in reality over the years. Given the complexity of accounting for these fluctuations across numerous variables, this poses a challenge.

The origins and destinations of truck are an essential part of the research. In this research an assumption that the catenary trucks shuttle between the two ports. The knowledge of the truck movements is crucial for the precise calculation of the SCBA and in making a decision on the implementation of an ERS infrastructure.

Further research is required for the decision making among the three routes, for example via a Multi-Criteria Analysis which can included the non-monetized variables as well. The study highlights numerous non-monetized variables that could heavily influence the route choice. The non-monetized value for the surrounding distribution centers is in favour of the Eastern route. Besides, the potential of the Eastern route as starting for an European network is more the be expected. Nonetheless, based on the NPV outcomes in this study using the chosen variables, the Eastern route appears to hold the most potential for the implementation of an ERS infrastructure.

8.2. Recommendations for further research

Based on the findings of this research, there are several recommendations that can be made for further research towards ERS (Electric Road System) infrastructure. These recommendations apply to research in the ERS field and specifically to the case study involving the ports of Rotterdam and Antwerp.

Recommendation further research on ERS

In this study, three key stakeholders are identified: transport companies, governmental bodies, and private investors. Among these stakeholders, transport companies play the most significant role as they are responsible for fulfilling all truck components in this research. The other prominent players are governmental entities or private investors. Their substantial investment is a must for the successful implementation of the ERS (Electric Road System) infrastructure. However, it's advisable to consider additional stakeholders beyond these primary ones. Energy providers and operators of ERS infrastructure should also be accounted for, given their potentially influential roles within this research. Their involvement and contributions could significantly impact the outcomes and viability of the proposed infrastructure.

Besides the benefits that occur towards the infrastructure and the truck cost (including emissions), the time savings for truck drivers could be taken into account in further research. This is one of the non-monetized directs effects of the policy measure. Due to the dynamic charging the do not have to find a charging station on the route, drive towards the charging station and charge its truck. Especially for a route like Rotterdam - Antwerp, in which the driver can takes it rest already while loading/unloading the truck within the port. It will not always be possible to charge the truck while loading/unloading, so this could results in a significant decrease of the labour hours for truck drivers.

Currently the power supply network throughout throughout the Netherlands is already fully occupied. In order to fulfill the needs for the ERS infrastructure to supply all trucks with electricity, research has to be done towards the feasibility for the power supply network as well. Besides the readiness and size of the power supply network it is also important to research the possibilities to build a high number of electric catenary trucks. It is not clear that if the ERS infrastructure is build the coming years, the need for raw materials for building batteries can fulfill the demand for the uptake of electric trucks.

The value for PM_v can be elaborated upon even more. Especially taken into account the wear of the tires under electric trucks, since electric trucks do weigh more compared to diesel trucks and other engine types. Besides the tire wear, also the catenary wear could be a cost effective element. As stated in the sensitivity analysis, the catenary lines do have a big influence in the final NPV. If the number of trucks using the ERS infrastructure is increasing, this would result in a shorter lifetime for these catenary lines, so the need for replacement will increase.

Recommendation further research on ERS towards case study port of Rotterdam - port of Antwerp

In this research the mean flows on the different routes have been used for the calculations, but instead it would be interesting to know precisely which part of this fleet is travel as shuttle service between the two ports. It is possible that a big part of the mean fleet is just travel on the route starting in Rotterdam towards another place in Europe. For these trucks the ERS infrastructure would not be the best solution in the beginning, since they would need a big battery to fulfill the rest of the journey. In fact it could help, but than the truck would be a hybrid version between for example catenary and (e-)diesel. This would only be profitable if the truck can be converted to a full electric catenary truck in the future if a European ERS infrastructure realized.

To create a more complete overview between the two ports it is recommended to take into account the different variables and policies of the Netherlands and Belgium. This would give a more complete overview for the two countries involved in this case study. The combination of variables for both countries would be a perfect estimation for other future projects which crosses boarders.

References

Ainalis, DT, C Thorne, and D Cebon (2020). *Decarbonising the UK's Long-Haul road freight at minimum economic cost.* Tech. rep. URL: `http://www.csrf.ac.uk/`.

Andersson, Matts et al. (n.d.). *CollERS2-Swedish German research collaboration on Electric Road Systems Opportunities for electric road systems in road freight economics A discussion paper from the CollERS2 project.* Tech. rep. URL: `https://electric-road-systems.eu/`.

ANWB (2023). "Diesel Price Netherlands". In.

Aronietis, Raimonds and Thierry Vanelslander (2021). *Economic Impacts of the Catenary Electric Road System Implementation in Flanders.* Tech. rep.

Aruldoss, Martin, T Miranda Lakshmi, and V Prasanna Venkatesan (2013). "A Survey on Multi Criteria Decision Making Methods and Its Applications". In: *American Journal of Information Systems* 1.1, pp. 31–43. DOI: `10.12691/ajis-1-1-5`. URL: `http://pubs.sciepub.com/ajis/1/1/5`.

Bateman, D. and Asociación Mundial de la Carretera. (2018). *ELECTRIC road systems : a solution for the future?* PIARC. ISBN: 9782840604969.

BNEF (2021). "Lithiom-Ion Battery Price Survey: Rising commodity prices starting to bite." In.

Bruyn, Sander de et al. (2023). *Handboek Milieuprijzen 2023.* Tech. rep. URL: `www.ce.nl`.

Burges, Karsten and Stefan Kippelt (2021). *GRID-RELATED CHALLENGES OF HIGH-POWER AND MEGAWATT CHARGING STATIONS FOR BATTERY-ELECTRIC LONG-HAUL TRUCKS.* Tech. rep.

Carbon Foodprint (2023). *CARBON FOOTPRINT COUNTRY SPECIFIC ELECTRICITY GRID GREENHOUSE GAS EMISSION FACTORS.* Tech. rep. URL: `www.carbonfootprint.com`.

CBS (2023). "Inflation since 2015". In.

CFI (n.d.). "Benefit-Cost Ratio (BCR)". In: ().

Chang, MF (2020). *Movares (2020). Verkenning Electric Road Systems.* Tech. rep.

Connolly, D (2017). "Economic viability of electric roads compared to oil and batteries for all forms of road transport". In: *Energy Strategy Reviews* 18, pp. 235–249. ISSN: 2211-467X. DOI: `https://doi.org/10.1016/j.esr.2017.09.005`. URL: `https://www.sciencedirect.com/science/article/pii/S2211467X17300469`.

De Saxe, Christopher et al. (2022). *ScienceDirect Vehicle and charging requirements for an electrified road freight system demonstrator in the UK-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0) Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference.* Tech. rep. URL: `www.sciencedirect.comwww.elsevier.com/locate/procedia2352-1465`.

Deshpande, Parth et al. (Sept. 2023). "A breakeven cost analysis framework for electric road systems". In: *Transportation Research Part D: Transport and Environment* 122. ISSN: 13619209. DOI: `10.1016/j.trd.2023.103870`.

Drevland Jakobsen, Pal, Jon Are Suul, and Torun Rise (2018). *Evaluation of constructability of dynamic charging systems for vehicles in Norway Appendix I.* Tech. rep.

Enexis (2023). "Tarieven elektriciteit voor zakelijk grootverbruik vanaf 01012023". In.

European Comission (2021). *EN.* Tech. rep.

Fabius, Bibi, Michiel Aldenkamp, and Ruud van Sloten (2020). *Transitiestudie verduurzaming wegtransport.* Tech. rep. URL: `www.evconsult.nl`.

Gaspars-Wieloch, Helena (Dec. 2019). "Project Net Present Value estimation under uncertainty". In: *Central European Journal of Operations Research* 27, pp. 179–197. DOI: `10.1007/s10100-017-0500-0`.

GeoWeb 5.5 (n.d.). "INWEVA". In: ().

Google Maps (n.d.). "Google Maps". In: ().

Gustavsson, Martin G H, Magnus Lindgren, and Moritz Mottschall (2020). *Real-world experiences of ERS Best practices from demonstration projects in Sweden and Germany Swedish-German research collaboration on Electric Road Systems.* Tech. rep. URL: `www.electricroads.org`.

Hacker, Florian et al. (2023). *CollERS2-Swedish German research collaboration on Electric Road Systems Expansion Strategies for Electric Road Systems (ERS) in Europe A working paper from the CollERS2 project.* Tech. rep.

Jöhrens, Julius et al. (2022). *Current technical findings on the eHighway system from field tests and accompanying research in Germany.* Tech. rep.

Julius Jöhrens, Authors et al. (2021). *Connecting Countries by Electric Roads Methodology for Feasibility Analysis of a Transnational ERS Corridor Swedish-German research collaboration on Electric Road Systems.* Tech. rep. URL: `www.electricroads.org`.

Klein, Anne et al. (2020). *STREAM Goederenvervoer 2020 Emissies van modaliteiten in het goederenvervoer-Versie 2.* Tech. rep. URL: `www.ce.nl`.

Kühnel, Sven (2018). *Oberleitungs-Lkw im Kontext weiterer Antriebs-und Energieversorgungsoptionen für den Straßengüterfernverkehr.* Tech. rep. URL: `www.oeko.de`.

M. Taljegard L. Thorson, M Odenberger and F Johnsson (2020). "Large-scale implementation of electric road systems: Associated costs and the impact on CO2 emissions". In: *International Journal of Sustainable Transportation* 14.8, pp. 606–619. DOI: `10.1080/15568318.2019.1595227`. URL: `https://doi.org/10.1080/15568318.2019.1595227`.

Mareev, Ivan, Jan Becker, and Dirk Uwe Sauer (Jan. 2018). "Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation". In: *Energies* 11.1. ISSN: 19961073. DOI: `10.3390/en11010055`.

Mareev, Ivan and Dirk Uwe Sauer (Dec. 2018). "Energy consumption and life cycle costs of overhead catenary heavy-duty trucks for long-haul transportation". In: *Energies* 11.12. ISSN: 19961073. DOI: `10.3390/en11123446`.

Morgan, Richard K (2012). "Environmental impact assessment: the state of the art". In: *Impact Assessment and Project Appraisal* 30.1, pp. 5–14. DOI: `10.1080/14615517.2012.661557`. URL: `https://doi.org/10.1080/14615517.2012.661557`.

Mouter, N. (2012). "Mouter_2012". In.

Mouter, Niek (2021). *New methods, reflections and applications domains in transport appraisal*, p. 288. ISBN: 9780323855594.

Mulder, Hans et al. (2022). "TNO-2022-P12044 (1)". In.

Netherlands Enterprise Agency (2022). *Electric Vehicles Statistics in the Netherlands.* Tech. rep.

Nykvist, Björn and Olle Olsson (2021). "The feasibility of heavy battery electric trucks". In: *Joule* 5.4, pp. 901–913. ISSN: 2542-4351. DOI: `https://doi.org/10.1016/j.joule.2021.03.007`. URL: `https://www.sciencedirect.com/science/article/pii/S2542435121001306`.

Patrick Plötz, Autoren et al. (2021). *Infrastruktur für Elektro-Lkw im Fernverkehr Hochleistungsschnelllader und Oberleitung im Vergleich-ein Diskussionspapier Impressum Infrastruktur für Elektro-Lkw im Fernverkehr.* Tech. rep.

PIARC (2023). *ELECTRIC ROAD SYSTEMS: A ROUTE TO NET ZERO A PIARC TECHNICAL REPORT TASK FORCE 2.2 ELECTRIC ROAD SYSTEMS.* ISBN: 9782840608073. URL: `http://www.piarc.org`.

Plötz, Patrick, Till Gnann, et al. (2019). "Impact of electric trucks powered by overhead lines on the European electricity system and CO2 emissions". In: *Energy Policy* 130, pp. 32–40. ISSN: 0301-4215. DOI: `https://doi.org/10.1016/j.enpol.2019.03.042`. URL: `https://www.sciencedirect.com/science/article/pii/S0301421519302150`.

Plötz, Patrick, Jakob Wachsmuth, et al. (2023). "Greenhouse gas emission budgets and policies for zero-Carbon road transport in Europe". In: *Climate Policy* 23.3, pp. 343–354. ISSN: 17527457. DOI: `10.1080/14693062.2023.2185585`.

Ramshankar, Arjun Thangaraj et al. (Mar. 2023). "Sustainability analysis of Overhead Cable Line powered freight trucks: A life cycle impact and techno-economic assessment toward transport electrification". In: *Environmental Research: Infrastructure and Sustainability.* DOI: `10.1088/2634-4505/acc273`.

Rijksoverheid (2020). *Rapport Werkgroep discontovoet 2020.* Tech. rep.

— (2023). "Vrachtwagenheffing 2026". In.

Rip, A (2001). "Technology Assessment". In: *International Encyclopedia of the Social & Behavioral Sciences.* Ed. by Neil J Smelser and Paul B Baltes. Oxford: Pergamon, pp. 15512–15515. ISBN: 978-0-08-043076-8. DOI: `https://doi.org/10.1016/B0-08-043076-7/03172-7`. URL: `https://www.sciencedirect.com/science/article/pii/B0080430767031727`.

Romijn, Gerbert and G. (Gusta) Renes (n.d.). *Algemene leidraad voor maatschappelijke kosten-batenanalyse.* ISBN: 9789058336194.

Saxe, Christopher de et al. (Oct. 2023). "An electric road system or big batteries: Implications for UK road freight". In: *Transportation Engineering*, p. 100210. ISSN: 2666691X. DOI: `10.1016/j.treng.2023.100210`. URL: `https://linkinghub.elsevier.com/retrieve/pii/S2666691X23000507`.

Scherrer, Aline (2023). “How media coverage of technologies affects public opinion: Evidence from alternative fuel vehicles in Germany”. In: *Environmental Innovation and Societal Transitions* 47, p. 100727. ISSN: 2210-4224. DOI: `https://doi.org/10.1016/j.eist.2023.100727`. URL: `https://www.sciencedirect.com/science/article/pii/S2210422423000370`.

Scherrer, Aline, Patrick Plötz, and Frank Van Laerhoven (2020). “Power from above? Assessing actor-related barriers to the implementation of trolley truck technology in Germany”. In: *Environmental Innovation and Societal Transitions* 34, pp. 221–236. ISSN: 2210-4224. DOI: `https://doi.org/10.1016/j.eist.2020.01.005`. URL: `https://www.sciencedirect.com/science/article/pii/S2210422420300150`.

Siemens (n.d.). “Expert knowledge, gathered via interview”. In: ().

Stütz, Sebastian et al. (2017). *Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw.* Tech. rep. URL: `http://www.isi.fraunhofer.de`.

Sundelin, Håkan et al. (2018). *Business case for electric road.* Tech. rep.

SWOV (2017). *Veilige bermen langs autosnelwegen: obstakelvrije zone, geleiderails of beide?* Tech. rep.

Tol, D. et al. (2023). *The potential of e-fuels for heavy duty road transport in the Netherlands TNO 2023 R10213 smartport.nl.* Tech. rep. URL: `www.smartport.nl`.

Tol, Dennis et al. (2022). *Techno-economic uptake potential of zero-emission trucks in Europe.* Tech. rep. URL: `www.tno.nl`.

Transport & Environment (2022). *Addressing the heavy-duty climate problem.* Tech. rep.

Van Ommeren, Kees et al. (2022). *PROJECTTEAM DECISIO.* Tech. rep. URL: `www.decisio.nl`.

VeiligeBerm (n.d.). “Infosheet-VeiligeBerm.nl-v1.0-1503102”. In: ().

Volvo Trucks (2019). “Welke gevolgen heeft het klimaatakkoord op de transportsector”. In.

Webinar (n.d.). “Webinar 34_ WSDOT Bridge Location Vertical Clearance”. In: ().

Zhang, Runsen, Shinichiro Fujimori, and Tatsuya Hanaoka (May 2018). “The contribution of transport policies to the mitigation potential and cost of 2 °c and 1.5 °c goals”. In: *Environmental Research Letters* 13.5. ISSN: 17489326. DOI: `10.1088/1748-9326/aabb0d`.

Zhao, Authors and Qian Fulton (2018). “UC Office of the President ITS reports Title A Comparison of Zero-Emission Highway Trucking Technologies Permalink https://escholarship.org/uc/item/1584b5z9 Publication Date”. In: DOI: `10.7922/G2FQ9TS7`. URL: `https://orcid.org/0000-0002-4245-0056`.

Appendix A

As described in chapters 4 and 5, multiple uptakes have been tested within the Social Cost Benefit Analysis. From the different tested uptakes, three have been selected and analysed in more depth. The results for the selected uptakes have been described in chapter 6.

The first comparison made is the one between the policy scenario and the zero alternative. In this comparison, the the uptake of the zero alternative is based on Fabius et al (2020). The uptake is visualized in figure 8.1. The policy scenario in this comparison can be seen in figure 8.2. It can be seen that till 2030 the electric trucks is only consisting of battery trucks. Between 2030 and 2054 the electric trucks consist most percentage of catenary trucks. In 2054 in total 70% of the trucks are electric trucks, from which 50% are catenary trucks in the policy scenario.

The second comparison is again made between the policy scenario and the zero alternative. In this scenario 'opportunity charging' is applied, as described in chapter 4. The figures 8.3 and 8.4 show the electric truck uptake for the zero alternative and the policy scenario. In 2054 the percentage of electric trucks is 83%, in both the zero alternative as the policy scenario. From the 83% electric trucks in the policy scenario in 2054, 60% are catenary trucks and 23% are battery trucks.

In the third comparison researched, the policy scenario is compared to the zero+ alternative. The electric truck uptake for the policy scenario is equal to the uptake of electric trucks in the first comparison, see figure 8.2. For the zero+ alternative the percentage of battery trucks in 2054 is set to 70%. The uptake is visualized in figure 8.5.

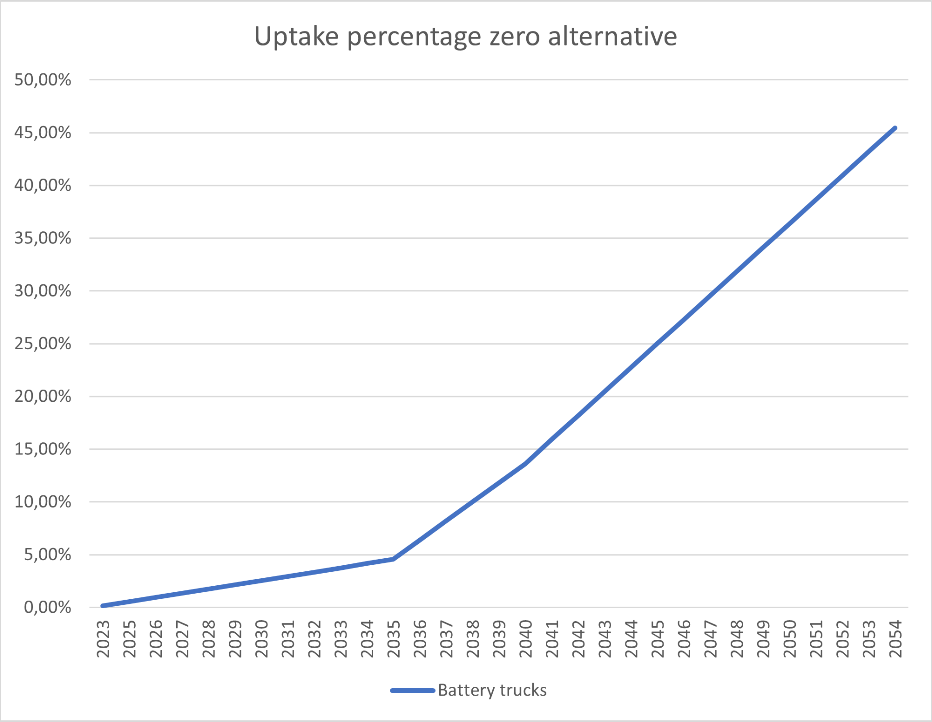

Figure 8.1: Uptake in the zero alternative, based on Fabius et al (2020)

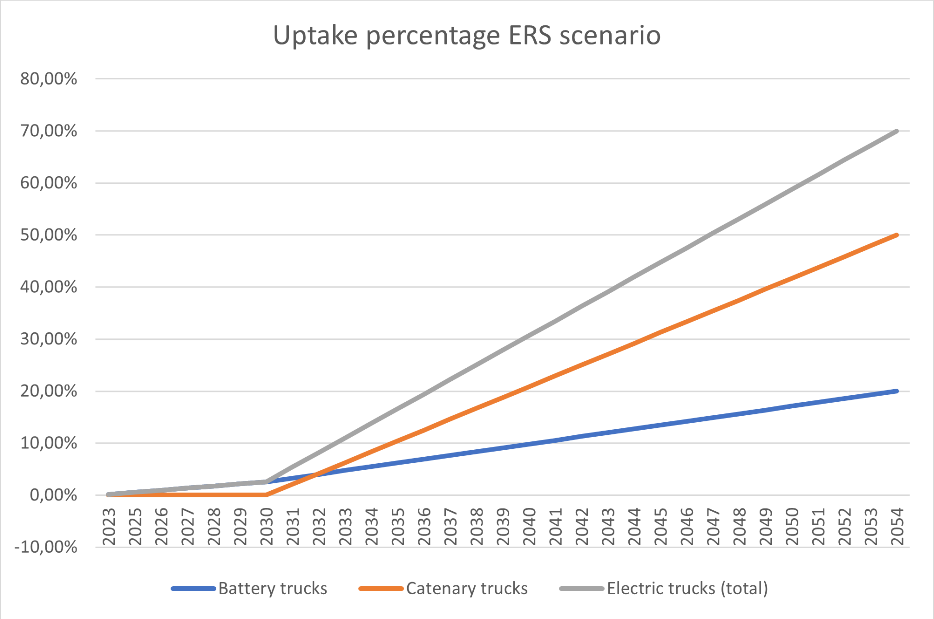

Figure 8.2: Uptake in the policy scenario

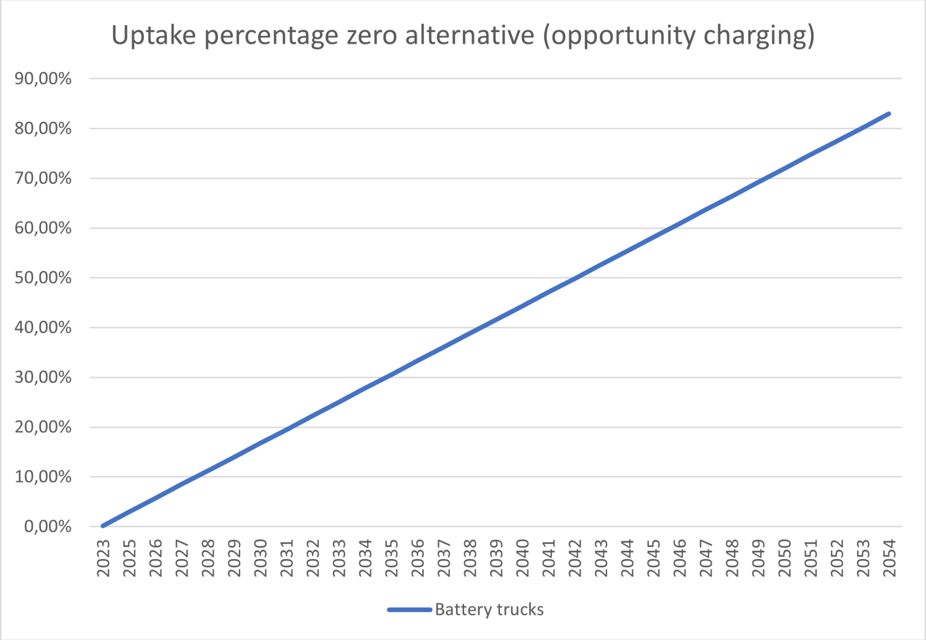

Figure 8.3: Opportunity charging uptake in the zero and zero+ alternatives, based on TNO (2022)

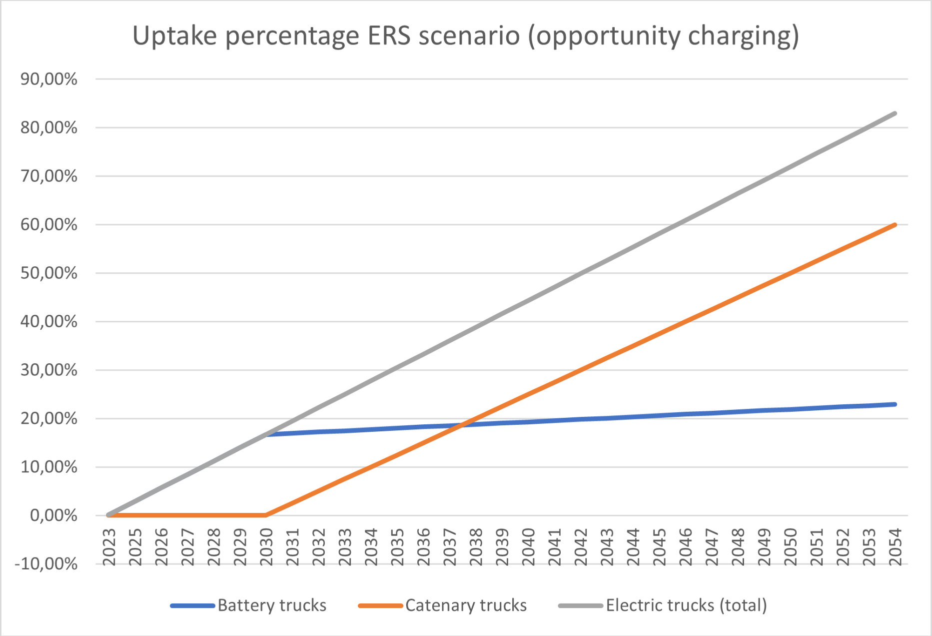

Figure 8.4: Opportunity charging uptake in the policy scenario, based on TNO (2022)

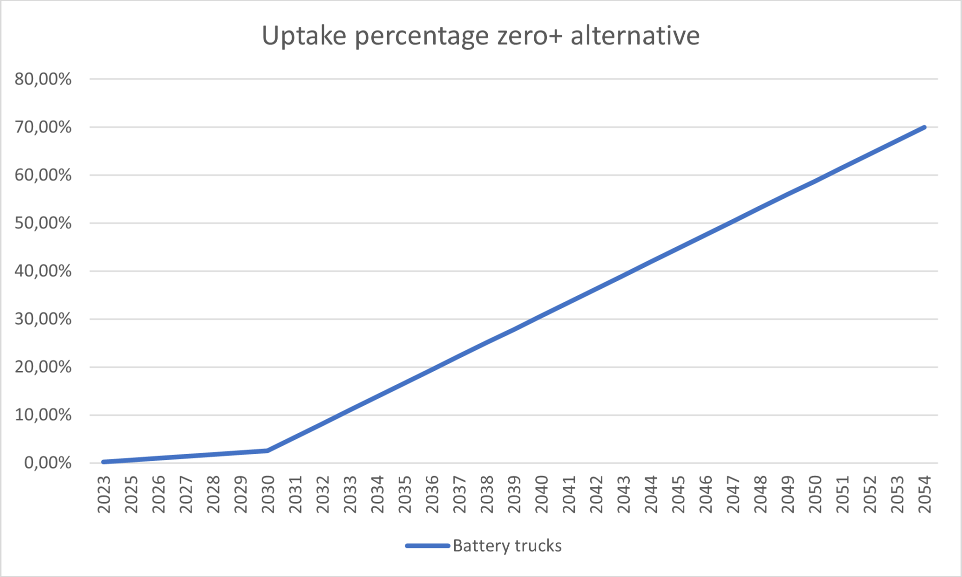

Figure 8.5: Uptake in the zero+ alternative

Appendix B

For the calculation of the ERS infrastructure, the cost from the report of Stutz et al (2017) are used. Table 8.2 shows the cost parameters for the different components within the ERS infrastructure construction. Since the report from Stutz et al (2017) is from the year 2017, the cost variables are corrected with an inflation percentage, this is explained in chapter 5.

Table 8.2: Kostenschätzung für die Oberleitungsinfrastruktur in der Variante 2A (HO-Lkw ohne Dieselmotor, Startphase, Best-Case-Betrachtung) (Stütz et al. 2017)

Komponente	**Berechnungsgrundlagen**	**Kosten [Euro/km]**
Energieeinspeisepunkt	ca. 15.000 Euro pro Anschluss; bei einem Anschlussraster von 3 km folgt daraus 5.000 Euro/km	5.000,–
Zuleitungen vom Energieeinspeisepunkt zur Umspannstation an der Strecke	ca. 50 Euro pro lfd. m Kabelgraben (Tiefbau, unbebautes Gebiet), ca. 100 Euro pro lfd. m Kabel; bei Ø 500 m Anschlusslänge ergeben sich Kosten von 75.000 Euro pro Anschluss; bei einem Anschlussraster von 3 km folgen daraus 25.000 Euro/km	25.000,–
Umspannstation	ca. 300.000 Euro pro MVA (inkl. Kommunikations- und Sicherheitstechnik); bei 3 MVA eistungsbedarf ergeben sich Kosten von 0,9 Mio. Euro pro Umspannstation; bei einem Raster von 3 km folgt daraus rund 0,3 Mio. Euro/km	300.000,–
Masten	ca. 10.000 Euro pro Mast (inkl. Ausleger und Fundament); bei einem Mastabstand von 50 m ergeben sich Kosten von 400.000 Euro pro km (für beide Fahrtrichtungen)	400.000,–
Oberleitung (Fahrdraht)	ca. 300 Euro pro lfd. m, d. h. 600.000 Euro pro km (für beide Fahrtrichtungen)	600.000,–
Passive Schutzeinrichtungen	Annahme: Es kann auf passive Schutzeinrichtungen verzichtet werden, da verformbare, gemäß DIN EN 12767 hinsichtlich der passiven Sicherheit geprüfte Tragkonstruktionen eingesetzt werden können	0,–
Querungen von Schilderbrücken und Überführungsbauwerken	Mehrkosten für Querungen von Schilderbrücken und Überführungsbauwerken stehen Einsparungen bei Masten entgegen	0,–
Projektierung, Planung, Ausschreibung, PM etc.	ca. 10 % der Investitionskosten	133.000,–
Gesamt		**1.463.000,–**

Appendix C

In Appendix C, the results for all tested uptakes are included in table form. Each comparison (policy scenario compared with zero(+) alternative) shows a table with the NPV results and B-C ratios for the uptakes taken into account. Besides, the Truck cost delta and Infrastructure cost delta are shown for the different uptakes. The result table is supported with the tables retrieved from the model. In these supporting tables, the Truck cost delta is split into nine elements, the nine elements are explained in depth in chapter 6.

Adjusting percentage policy scenario (70%) compared to zero alternative

Zero uptake: 0,16% - 3% (2030) - 14% (2040) - 46% (2054) The first comparison is between the policy scenario and the zero alternative. Where the zero alternative follows the uptake of Fabius et al (2020) and the policy scenario contains 70% of electric trucks in 2054. The percentage of catenary trucks differs per calculation. As shown in the table below, in the first calculation the percentage of catenary trucks is 40% (40% ERS in the table), 50% in the second calculation and 60% in the third calculation.
The calculation of the policy scenario with 50% of catenary trucks is analysed and evaluated in depth in this research and can be read in chapter 6.

Uptake	0,16 - 70 (**40% ERS**)	0,16 - 70 (**50% ERS**)	0,16 - 70 (**60% ERS**)
NPV	996	1,087	1,177
B-C ratio	3.7	3.9	4.2
NPV	1,252	1,358	1,462
B-C ratio	4.2	4.5	4.9
NPV	2,189	2,355	2,521
B-C ratio	5.3	5.6	6.1
Truck cost delta (mln. euro)	1,281	1,365	1,447
Infrastructure cost delta (mln. euro)	-285	-278	-270
Truck cost delta (mln. euro)	1,541	1,638	1,735
Infrastructure cost delta (mln. euro)	-289	-281	-272
Truck cost delta (mln. euro)	2,524	2,678	2,831
Infrastructure cost delta (mln. euro)	-335	-323	-310

Zero alternative (0,16% - 3% - 46%), policy (0,16% - 3% - **70% / 40% ERS**): Truck cost

West	**Million**	
Investment cost	162,5288342	162528834,2
Maintenance cost	59,58941917	59589419,17
Residual cost	-19,85164364	-19851643,64
Energy cost	396,8903849	396890384,9
	599,1569946	
CO2 emissions	510,7691922	510769192,2
NOx emissions	62,80212449	62802124,49
PMv emissions	2,995119078	2995119,078
	576,5664358	
Truck levies	176,8651312	176865131,2
Tariff ERS	-71,15753967	-71157539,67
	105,7075916	
total West	1281,431022	1281431022
Middle	**Million**	
Investment cost	174,8965533	174896553,3
Maintenance cost	64,08316624	64083166,24
Residual cost	-23,62614446	-23626144,46
Energy cost	502,7940189	502794018,9
	718,147594	
CO2 emissions	629,30691	629306910
NOx emissions	77,37287137	77372871,37
PMv emissions	3,690017895	3690017,895
	710,3697993	
Truck levies	190,2040228	190204022,8
Tariff ERS	-77,77539928	-77775399,28
	112,4286235	
total	1540,946017	1540946017
East	**Million**	
Investment cost	276,2885524	276288552,4
Maintenance cost	101,2623009	101262300,9
Residual cost	-37,31979285	-37319792,85
Energy cost	830,006367	830006367
	1170,237427	
CO2 emissions	1059,351268	1059351268
NOx emissions	130,2627737	130262773,7
PMv emissions	6,212409564	6212409,564
	1195,826452	
Truck levies	300,5593423	300559342,3
Tariff ERS	-142,7080093	-142708009,3
	157,851333	
Total	2523,915212	2523915212

Zero alternative (0,16% - 3% - 46 policy (0,16% - 3% - **70% / 50% ERS**): Truck cost
Discussed in chapter 6

West	**Million**	
Investment cost	214,2430861	214243086,1
Maintenance cost	61,80306482	61803064,82
Residual cost	-22,03902674	-22039026,74
Energy cost	409,1163414	409116341,4
	663,1234655	
CO2 emissions	529,9570439	529957043,9
NOx emissions	62,8094252	62809425,2
PMv emissions	2,99546726	2995467,26
	595,7619363	
Truck levies	176,8856917	176885691,7
Tariff ERS	-71,1575652	-71157565,2
	105,7281265	
total West	1364,613528	1364613528
Middle	**Million**	
Investment cost	230,4916758	230491675,8
Maintenance cost	66,46523346	66465233,46
Residual cost	-26,55821592	-26558215,92
Energy cost	521,3243183	521324318,3
	791,7230116	
CO2 emissions	652,9294522	652929452,2
NOx emissions	77,38391282	77383912,82
PMv emissions	3,690544477	3690544,477
	734,0039095	
Truck levies	190,2311658	190231165,8
Tariff ERS	-77,7762541	-77776254,1
	112,4549117	
total	1638,181833	1638181833
East	**Million**	
Investment cost	363,9093759	363909375,9
Maintenance cost	105,0206365	105020636,5
Residual cost	-41,90916701	-41909167,01
Energy cost	857,037152	857037152
	1284,057997	
CO2 emissions	1099,08105	1099081050
NOx emissions	130,2735542	130273554,2
PMv emissions	6,2129237	6212923,7
	1235,567528	
Truck levies	300,5842164	300584216,4
Tariff ERS	-142,707811	-142707811
	157,8764055	
total	2677,501931	2677501931

Zero alternative (0,16% - 3% - 46%), policy (0,16% - 3% - **70% / 60% ERS**): Truck cost

West	**Million**	
Investment cost	265,7109503	265710950,3
Maintenance cost	64,0047756	64004775,6
Residual cost	-24,20740753	-24207407,53
Energy cost	421,2623843	421262384,3
	726,7707027	
CO2 emissions	549,0337262	549033726,2
NOx emissions	62,80375757	62803757,57
PMv emissions	2,995196962	2995196,962
	614,8326808	
Truck levies	176,8697304	176869730,4
Tariff ERS	-71,15597267	-71155972,67
	105,7137577	
total West	1447,317141	1447317141
Middle	**Million**	
Investment cost	285,6748828	285674882,8
Maintenance cost	68,84121885	68841218,85
Residual cost	-29,4325604	-29432560,4
Energy cost	539,8069358	539806935,8
	864,890477	
CO2 emissions	676,4970802	676497080,2
NOx emissions	77,38825484	77388254,84
PMv emissions	3,690751554	3690751,554
	757,5760866	
Truck levies	190,2418397	190241839,7
Tariff ERS	-77,77619844	-77776198,44
	112,4656412	
total	1734,932205	1734932205
East	**Million**	
Investment cost	451,6983008	451698300,8
Maintenance cost	108,7526632	108752663,2
Residual cost	-46,53246914	-46532469,14
Energy cost	883,8508242	883850824,2
	1397,769319	
CO2 emissions	1138,559236	1138559236
NOx emissions	130,2486141	130248614,1
PMv emissions	6,211734273	6211734,273
	1275,019585	
Truck levies	300,5266714	300526671,4
Tariff ERS	-142,7032726	-142703272,6
	157,8233988	
total	2830,612302	2830612302

Adjusting percentage policy scenario (80%) compared to zero alternative

Zero uptake: 0,16% - 3% (2030) - 14% (2040) - 46% (2054) The second comparison is again between the policy scenario and the zero alternative. In this calculation the zero alternative follows the uptake of Fabius et al (2020) and the policy scenario contains 80% of electric trucks in 2054. The percentage of catenary trucks differs in 2054 is 50%.

Percentage	0,16 - **80** (**50% ERS**)
NPV	1,402
B/C ratio	4.7
NPV	1,738
B/C ratio	5.4
NPV	2.991
B/C ratio	6.7
Truck savings	1.688
Infra savings	-285
Truck savings	2,027
Infra savings	-289
Truck savings	3,326
Infra savings	-335

Zero alternative (0,16% - 3% - 46%), policy (0,16% - 3% - **80% / 50% ERS**): Truck cost

West	**Million**	
Investment cost	208,2793599	208279359,9
Maintenance cost	77,25137869	77251378,69
Residual cost	-27,32197115	-27321971,15
Energy cost	515,0749625	515074962,5
	773,2837299	
CO2 emissions	668,8633773	668863377,3
NOx emissions	81,92300736	81923007,36
PMv emissions	3,907020094	3907020,094
	754,6934048	
Truck levies	230,713906	230713906
Tariff ERS	-71,1575652	-71157565,2
	159,5563408	
total West	1687,533476	1687533476
Middle	**Million**	
Investment cost	223,8714189	223871418,9
Maintenance cost	83,07738527	83077385,27
Residual cost	-32,21920023	-32219200,23
Energy cost	651,8566231	651856623,1
	926,586227	
CO2 emissions	824,0493769	824049376,9
NOx emissions	100,9302737	100930273,7
PMv emissions	4,813502581	4813502,581
	929,7931532	
Truck levies	248,1146653	248114665,3
Tariff ERS	-77,7762541	-77776254,1
	170,3384111	
total	2026,717791	2026717791
East	**Million**	
Investment cost	353,8901584	353890158,4
Maintenance cost	131,2718763	131271876,3
Residual cost	-50,90100402	-50901004,02
Energy cost	1076,804419	1076804419
	1511,06545	
CO2 emissions	1387,167068	1387167068
NOx emissions	169,9167628	169916762,8
PMv emissions	8,103562452	8103562,452
	1565,187393	
Truck levies	392,0542224	392054222,4
Tariff ERS	-142,707811	-142707811
	249,3464114	
total	3325,599254	3325599254

Policy scenario compared to zero alternative with opportunity charging

(Opportunity also in zero alternative) 25% increase per 10 years

Zero uptake: 0,16% – 17% (2030) - 44% (2040) 83% (2054) The comparison between the policy scenario and the zero alternative is tested for the third time, including opportunity charging. The zero alternative contains 83% of electric trucks in 2054, same counts for the policy scenario. The percentage of catenary trucks differs per calculation. As shown in the table below, in the first calculation the percentage of catenary trucks is 50% (50% ERS in the table), 60% in the second calculation and 65% in the third calculation.
The calculation of the policy scenario with 60% of catenary trucks is analysed and evaluated in depth in this research and can be read in chapter 6.

Uptake	ERS 50%	**ERS 60%**	ERS 65%
NPV	76	166	212
B/C ratio	1.2	1.5	1.6
NPV	137	242	295
B/C ratio	1.4	1.7	1.8
NPV	319	485	568
B/C ratio	1.7	2.0	2.2
Truck savings	344	427	469
Infra savings	-268	-261	-257
Truck savings	408	505	553
Infra savings	-270	-262	-258
Truck savings	626	779	856
Infra savings	-307	-294	-288

Zero alternative (0,16% - 17% - 44% - 83%) , policy (0,16% - 17% - 44% - 83% / **50% ERS**): Truck cost

West	**Million**	
Investment cost	258,126797	258126797
Maintenance cost	11,06932454	11069324,54
Residual cost	-10,9194782	-10919478,2
Energy cost	61,13809528	61138095,28
	319,4147386	
CO2 emissions	95,86224558	95862245,58
NOx emissions	0,038593325	38593,32528
PMv emissions	0,001840568	1840,568385
	95,90267947	
Truck levies	0,108687622	108687,6216
Tariff ERS	-71,1575652	-71157565,2
	-71,04887758	
total West	344,2685405	344268540,5
Middle	**Million**	
Investment cost	277,4889473	277488947,3
Maintenance cost	11,89873974	11898739,74
Residual cost	-14,57127404	-14571274,04
Energy cost	92,56046715	92560467,15
	367,3768802	
CO2 emissions	118,0609905	118060990,5
NOx emissions	0,040389425	40389,42486
PMv emissions	0,001926227	1926,226827
	118,1033061	
Truck levies	0,099288432	99288,43211
Tariff ERS	-77,7762541	-77776254,1
	-77,67696567	
total	407,8032207	407803220,7
East	**Million**	
Investment cost	438,5613783	438561378,3
Maintenance cost	18,79153242	18791532,42
Residual cost	-23,03172361	-23031723,61
Energy cost	135,1537396	135153739,6
	569,4749267	
CO2 emissions	198,6383934	198638393,4
NOx emissions	0,055005139	55005,13906
PMv emissions	0,00262327	2623,270196
	198,6960218	
Truck levies	0,126915065	126915,0652
Tariff ERS	-142,707811	-142707811
	-142,5808959	
total	625,5900525	625590052,5

Zero alternative (0,16% - 17% - 44% - 83%) , policy (0,16% - 17% - 44% - 83% / **60% ERS**): Truck cost
Discussed in chapter 6

West	**Million**	
Investment cost	309,5890681	309589068,1
Maintenance cost	13,27264843	13272648,43
Residual cost	-13,08736777	-13087367,77
Energy cost	73,29520234	73295202,34
	383,0695511	
CO2 emissions	114,9600214	114960021,4
NOx emissions	0,034921516	34921,51638
PMv emissions	0,001665455	1665,454804
	114,9966084	
Truck levies	0,098346969	98346,96879
Tariff ERS	-71,15597267	-71155972,67
	-71,0576257	
total West	427,0085339	427008533,9
Middle	**Million**	
Investment cost	332,989493	332989493
Maintenance cost	14,27059642	14270596,42
Residual cost	-17,47816466	-17478164,66
Energy cost	111,0106426	111010642,6
	440,7925674	
CO2 emissions	141,5831239	141583123,9
NOx emissions	0,038879314	38879,31386
PMv emissions	0,001854208	1854,207571
	141,6238574	
Truck levies	0,09557616	95576,15956
Tariff ERS	-77,77619844	-77776198,44
	-77,68062228	
total	504,7358025	504735802,5
East	**Million**	
Investment cost	526,206339	526206339
Maintenance cost	22,53051443	22530514,43
Residual cost	-27,63350247	-27633502,47
Energy cost	162,0256397	162025639,7
	683,1289907	
CO2 emissions	238,1848445	238184844,5
NOx emissions	0,040568597	40568,59746
PMv emissions	0,001934772	1934,771813
	238,2273479	
Truck levies	0,093605185	93605,1845
Tariff ERS	-142,7032726	-142703272,6
	-142,6096674	
total	778,7466711	778746671,1

Zero alternative (0,16% - 17% - 44% - 83%) , policy (0,16% - 17% - 44% - 83% / **65% ERS**): Truck cost

West	**Million**	
Investment cost	335,4402619	335440261,9
Maintenance cost	14,38893229	14388932,29
Residual cost	-14,18096191	-14180961,91
Energy cost	79,47252074	79472520,74
	415,120753	
CO2 emissions	124,6191461	124619146,1
NOx emissions	0,049767577	49767,57726
PMv emissions	0,002373484	2373,483721
	124,6712872	
Truck levies	0,140156868	140156,8682
Tariff ERS	-71,15957795	-71159577,95
	-71,01942108	
total West	468,7726191	468772619,1
Middle	**Million**	
Investment cost	360,658729	360658729
Maintenance cost	15,44664637	15446646,37
Residual cost	-18,92991403	-18929914,03
Energy cost	120,1580875	120158087,5
	477,3335488	
CO2 emissions	153,2818339	153281833,9
NOx emissions	0,023726504	23726,504
PMv emissions	0,001131549	1131,549376
	153,3066919	
Truck levies	0,058326341	58326,34137
Tariff ERS	-77,77602162	-77776021,62
	-77,71769528	
total	552,9225455	552922545,5
East	**Million**	
Investment cost	570,0179498	570017949,8
Maintenance cost	24,41371977	24413719,77
Residual cost	-29,92908682	-29929086,82
Energy cost	175,5738178	175573817,8
	740,0764006	
CO2 emissions	258,0940506	258094050,6
NOx emissions	0,050758818	50758,81813
PMv emissions	0,002420757	2420,757352
	258,1472302	
Truck levies	0,117117397	117117,397
Tariff ERS	-142,7114579	-142711457,9
	-142,5943405	
total	855,6292903	855629290,3

Adjusting percentage policy scenario (70%) compared to zero+ alternative

Zero+ uptake: 0,16% - 70% (2030: 3% battery) Followed up, the next comparison is between the policy scenario and the zero+ alternative. Within the zero+ alternative, the final number of trucks consists of 70% electric trucks in 2054. The percentage of catenary trucks within the policy scenario differ per calculation. As shown in the table below, in the first calculation the percentage of catenary trucks is 40% (40% ERS in the table), 50% in the second calculation and 60% in the third calculation.

The calculation of the policy scenario with 50% of catenary trucks is analysed and evaluated in depth in this research and can be read in chapter 6.

Percentage	0,16 - 70 (**40% ERS**)	0,16 - 70 (**50% ERS**)	0,16 – 70 (**60% ERS**)
NPV	60	151	241
B/C ratio	1.2	1.6	1.9
NPV	112	217	322
B/C ratio	1.4	1.8	2.2
NPV	280	445	611
B/C ratio	1.8	2.3	2.8
Truck savings	261	334	427
Infra savings	-201	-194	-186
Truck savings	311	408	505
Infra savings	-199	-191	-183
Truck savings	472	625	779
Infra savings	-192	-180	-167

Zero+ alternative (0,16% - 3% - 70%) , policy (0,16% - 3% - **70% / 40% ERS**): Truck cost

West	**Million**	
Investment cost	206,4178882	206417888,2
Maintenance cost	8,849271561	8849271,561
Residual cost	-8,731659747	-8731659,747
Energy cost	48,86819157	48868191,57
	255,4036916	
CO2 emissions	76,61518734	76615187,34
NOx emissions	0,023365077	23365,07725
PMv emissions	0,001114312	1114,312441
	76,63966673	
Truck levies	0,065801396	65801,39585
Tariff ERS	-71,15753967	-71157539,67
	-71,09173827	
total West	260,9516201	260951620,1
Middle	**Million**	
Investment cost	222,07065	222070650
Maintenance cost	9,511479235	9511479,235
Residual cost	-11,66269035	-11662690,35
Energy cost	73,98936073	73989360,73
	293,9087996	
CO2 emissions	94,39890539	94398905,39
NOx emissions	0,021986903	21986,90348
PMv emissions	0,001048585	1048,585452
	94,42194088	
Truck levies	0,05404992	54049,91979
Tariff ERS	-77,77539928	-77775399,28
	-77,72134936	
total	310,6093911	310609391,1
East	**Million**	
Investment cost	350,7841233	350784123,3
Maintenance cost	15,03140224	15031402,24
Residual cost	-18,41970466	-18419704,66
Energy cost	108,1079312	108107931,2
	455,5037521	
CO2 emissions	158,882357	158882357
NOx emissions	0,04151461	41514,60992
PMv emissions	0,001979888	1979,888439
	158,9258515	
Truck levies	0,095787948	95787,94843
Tariff ERS	-142,7080093	-142708009,3
	-142,6122213	
total	471,8173822	471817382,2

Zero+ alternative (0,16% - 3% - 70%) , policy (0,16% - 3% - **70% / 50% ERS**): Truck cost
Discussed in chapter 6

West	**Million**	
Investment cost	258,1321402	258132140,2
Maintenance cost	11,06291721	11062917,21
Residual cost	-10,91904285	-10919042,85
Energy cost	61,09414797	61094147,97
	319,3701625	
CO2 emissions	95,80303901	95803039,01
NOx emissions	0,030665793	30665,7929
PMv emissions	0,001462494	1462,49354
	95,83516729	
Truck levies	0,086361879	86361,87915
Tariff ERS	-71,1575652	-71157565,2
	-71,07120332	
total West	344,1341265	344134126,5
Middle	**Million**	
Investment cost	277,6657724	277665772,4
Maintenance cost	11,89354645	11893546,45
Residual cost	-14,59476181	-14594761,81
Energy cost	92,51966013	92519660,13
	367,4842172	
CO2 emissions	118,0214475	118021447,5
NOx emissions	0,03302836	33028,35961
PMv emissions	0,001575168	1575,167573
	118,056051	
Truck levies	0,081192888	81192,88781
Tariff ERS	-77,7762541	-77776254,1
	-77,69506122	
total	407,845207	407845207
East	**Million**	
Investment cost	438,4049468	438404946,8
Maintenance cost	18,78973788	18789737,88
Residual cost	-23,00907881	-23009078,81
Energy cost	135,1387162	135138716,2
	569,3243221	
CO2 emissions	198,6121384	198612138,4
NOx emissions	0,052295106	52295,10648
PMv emissions	0,002494025	2494,025041
	198,6669275	
Truck levies	0,120662123	120662,1229
Tariff ERS	-142,707811	-142707811
	-142,5871488	
total	625,4041007	625404100,7

Zero+ alternative (0,16% - 3% - 70%) , policy (0,16% - 3% - **70% / 60% ERS**): Truck cost

West	**Million**	
Investment cost	309,6000044	309600004,4
Maintenance cost	13,264628	13264628
Residual cost	-13,08742364	-13087423,64
Energy cost	73,24019093	73240190,93
	383,0173997	
CO2 emissions	114,8797214	114879721,4
NOx emissions	0,02499816	24998,15973
PMv emissions	0,001192196	1192,196374
	114,9059117	
Truck levies	0,070400529	70400,52923
Tariff ERS	-71,15597267	-71155972,67
	-71,08557214	
total West	426,8377393	426837739,3
Middle	**Million**	
Investment cost	332,8489795	332848979,5
Maintenance cost	14,26953185	14269531,85
Residual cost	-17,46910629	-17469106,29
Energy cost	111,0022776	111002277,6
	440,6516826	
CO2 emissions	141,5890755	141589075,5
NOx emissions	0,037370378	37370,37839
PMv emissions	0,001782244	1782,244378
	141,6282282	
Truck levies	0,091866777	91866,77679
Tariff ERS	-77,77619844	-77776198,44
	-77,68433167	
total	504,5955791	504595579,1
East	**Million**	
Investment cost	526,1938717	526193871,7
Maintenance cost	22,52176456	22521764,56
Residual cost	-27,63238095	-27632380,95
Energy cost	161,9523884	161952388,4
	683,0356437	
CO2 emissions	238,0903247	238090324,7
NOx emissions	0,027355005	27355,00476
PMv emissions	0,001304598	1304,597533
	238,1189843	
Truck levies	0,063117052	63117,05182
Tariff ERS	-142,7032726	-142703272,6
	-142,6401556	
total	778,5144725	778514472,5

Adjusting percentage policy scenario (80%) compared to zero+ alternative

Zero+ uptake: 0,16% - 70% (2030: 3% battery) Finally, another comparison is made between the policy scenario and the zero+ alternative. Within the zero+ alternative, the final number of trucks consists of 80% electric trucks in 2054. The percentage of catenary trucks within the policy scenario is 50%.

Percentage	0,16 - **80** (**50% ERS**)
NPV	466
B/C ratio	2.6
NPV	597
B/C ratio	3.0
NPV	1,081
B/C ratio	4.0
Truck savings	667
Infra savings	-201
Truck savings	796
Infra savings	-199
Truck savings	1,274
Infra savings	-192

Zero+ alternative (0,16% - 3% - 70%) , policy (0,16% - 3% - **80% / 50% ERS**): Truck cost

West	**Million**	
Investment cost	252,168414	252168414
Maintenance cost	26,51123108	26511231,08
Residual cost	-16,20198726	-16201987,26
Energy cost	167,0527691	167052769,1
	429,5304269	
CO2 emissions	234,7093725	234709372,5
NOx emissions	19,14424795	19144247,95
PMv emissions	0,913015328	913015,3277
	254,7666358	
Truck levies	53,91457619	53914576,19
Tariff ERS	-71,1575652	-71157565,2
	-17,24298901	
total West	667,0540737	667054073,7
Middle	**Million**	
Investment cost	271,0455155	271045515,5
Maintenance cost	28,50569827	28505698,27
Residual cost	-20,25574612	-20255746,12
Energy cost	223,0519649	223051964,9
	502,3474326	
CO2 emissions	289,1413723	289141372,3
NOx emissions	23,57938923	23579389,23
PMv emissions	1,124533272	1124533,272
	313,8452948	
Truck levies	57,96469238	57964692,38
Tariff ERS	-77,7762541	-77776254,1
	-19,81156173	
total	796,3811656	796381165,6
East	**Million**	
Investment cost	428,3857293	428385729,3
Maintenance cost	45,04097767	45040977,67
Residual cost	-32,00091582	-32000915,82
Energy cost	354,9059833	354905983,3
	796,3317745	
CO2 emissions	486,6981563	486698156,3
NOx emissions	39,69550365	39695503,65
PMv emissions	1,893132777	1893132,777
	528,2867927	
Truck levies	91,59066806	91590668,06
Tariff ERS	-142,707811	-142707811
	-51,1171429	
total	1273,501424	1273501424

Appendix D

In chapter 6 the sensitivity analysis is performed. In tables 8.3, 8.4 and 8.5, the results for the sensitivity analysis for the Western routes, Middle route and Eastern route are shown again in table form. The numbers show the percentage change of the Net Present Value (NPV) outcome. The explanation on the numbers can be read in chapter 6.

Table 8.3: Sensitivity analysis percentage delta from initial NPV West

	Zero (opportunity charging)		Zero+	
Component	166 million		155 million	
Percentage change in variable	**-10%**	**+10%**	**-10%**	**+10%**
Catenary lines cost	-18	20	-27	22
Possible ERS distance	31		32	
Mean number of trucks	-31	32	-34	32
Energy consumption catenary trucks	34	-33	30	-30
Electricity cost ERS	38	-38	34	-35
CO2 emission cost	-42	16	-39	15
Electricity cost charging station	-42	43	-39	38
Energy consumption battery trucks	-66	66	-61	60

Table 8.4: Sensitivity analysis percentage delta from initial NPV Middle

	Zero (opportunity charging)		Zero+	
Component	242 million		217 million	
Percentage change in variable	**-10%**	**+10%**	**-10%**	**+10%**
Catenary lines cost	-17	14	-19	16
Possible ERS distance	22		24	
Mean number of trucks	-25	25	-27	27
Energy consumption catenary trucks	28	-28	26	-26
Electricity cost ERS	31	-31	29	-29
CO2 emission cost	-36	14	-34	12
Electricity cost charging station	-36	36	-33	33
Energy consumption battery trucks	-54	55	-51	50

Table 8.5: Sensitivity analysis percentage delta from initial NPV East

	Zero (opportunity charging)		Zero+	
Component	335 million		262 million	
Percentage change in variable	**-10%**	**+10%**	**-10%**	**+10%**
Energy consumption catenary trucks	24	-24	21	-21
CO2 emission cost	-30	11	-27	10
Electricity cost ERS	27	-27	24	-24
Electricity cost charging station	-30	30	-27	27
Energy consumption battery trucks	-46	46	-42	42

Appendix E

After the sensitivity analysis performed towards all variables, the five most influencing variables have been tested on its sensitivity in more depth. In chapter 6, the sensitivity analysis in more depth for the variables Energy consumption battery trucks and CO_2 cost, comparing the policy scenario with the zero alternative (including opportunity charging) are shown and explained. In Appendix E the figures are shown for all five most influencing variables: Energy consumption battery trucks, Energy consumption catenary trucks, Electricity cost charging station, Electricity cost ERS and CO_2 cost. The variables for the comparison between the policy scenario and zero alternative (including opportunity charging) and the comparison between the policy scenario and the zero+ alternative are visualized.

Policy scenario - Zero alternative with opportunity charging

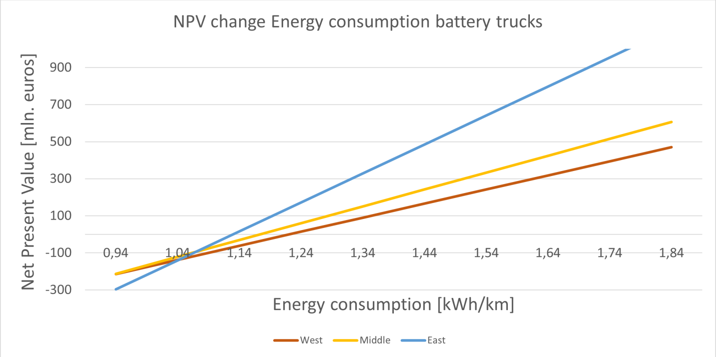

Figure 8.6: Sensitivity analysis NPV results for the direct effect: Energy consumption battery trucks (policy scenario - zero alternative with opportunity charging)

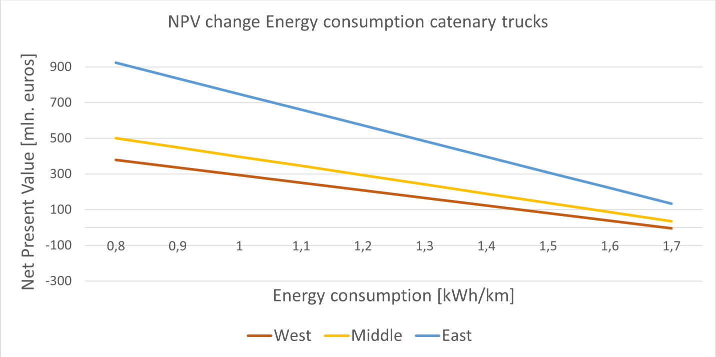

Figure 8.7: Sensitivity analysis NPV results for the direct effect: Energy consumption catenary trucks (policy scenario - zero alternative with opportunity charging)

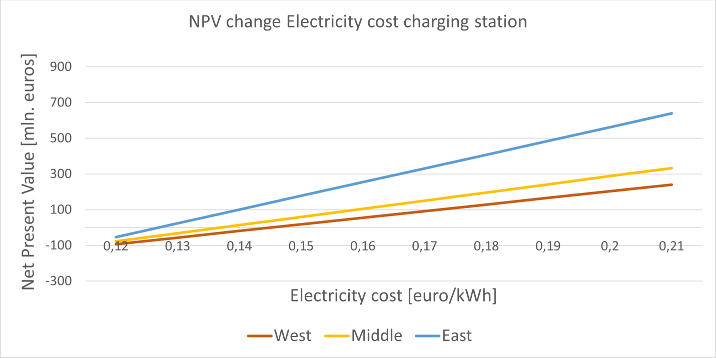

Figure 8.8: Sensitivity analysis NPV results for the direct effect: Electricity cost charging station (policy scenario - zero alternative with opportunity charging)

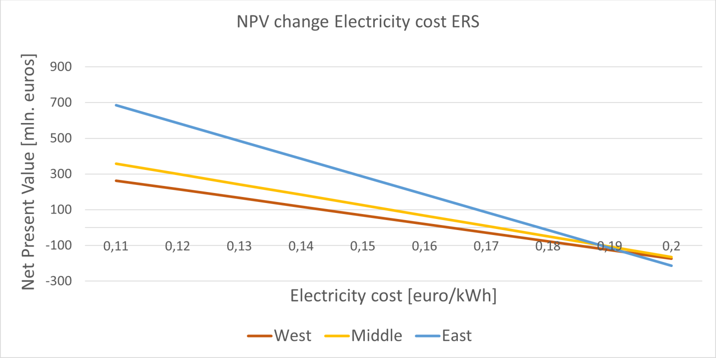

Figure 8.9: Sensitivity analysis NPV results for the direct effect: Electricity cost ERS (policy scenario - zero alternative with opportunity charging)

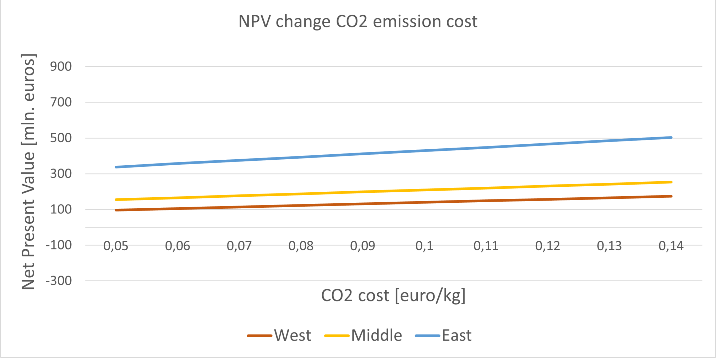

Figure 8.10: Sensitivity analysis NPV results for the direct effect: CO_2 cost (policy scenario - zero alternative with opportunity charging)

Policy scenario - Zero+ alternative

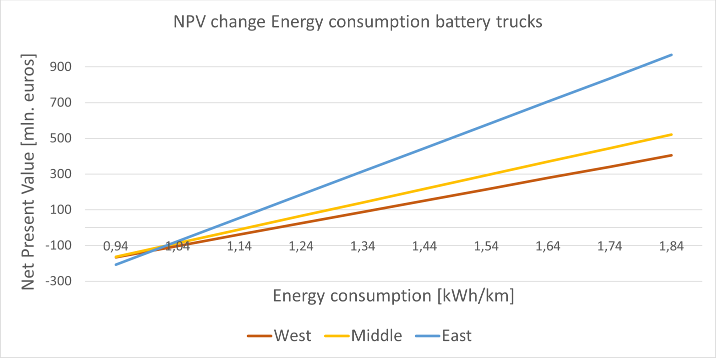

Figure 8.11: Sensitivity analysis NPV results for the direct effect: Energy consumption battery trucks (policy scenario - zero+ alternative)

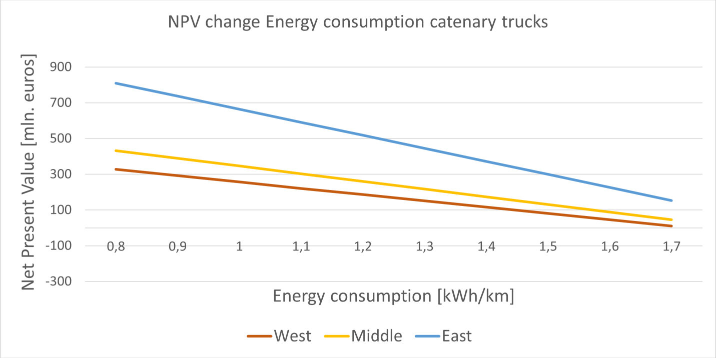

Figure 8.12: Sensitivity analysis NPV results for the direct effect: Energy consumption catenary trucks (policy scenario - zero+ alternative)

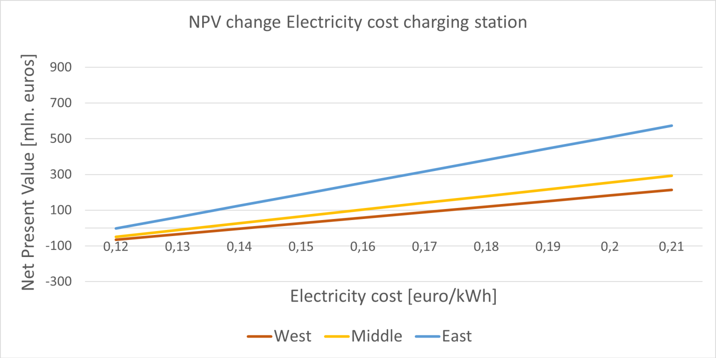

Figure 8.13: Sensitivity analysis NPV results for the direct effect: Electricity cost charging station (policy scenario - zero+ alternative)

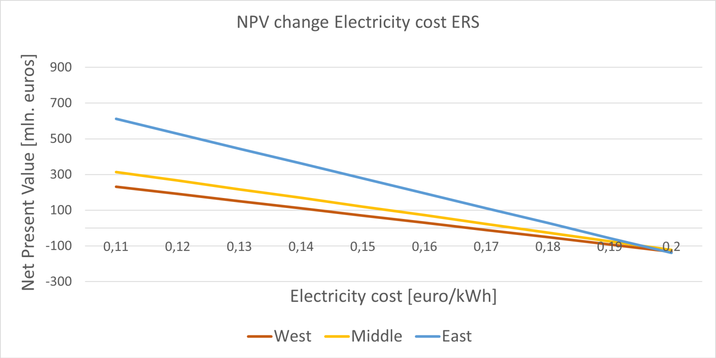

Figure 8.14: Sensitivity analysis NPV results for the direct effect: Electricity cost ERS (policy scenario - zero+ alternative)

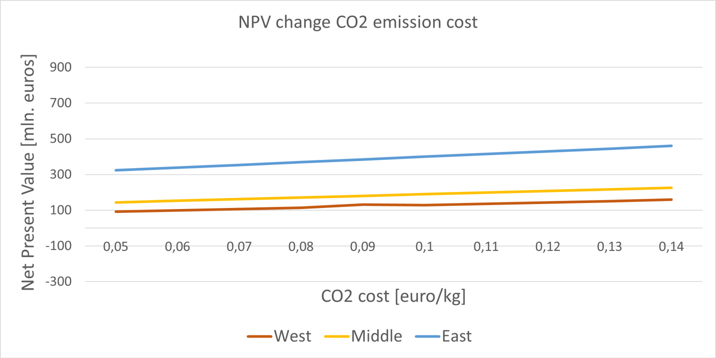

Figure 8.15: Sensitivity analysis NPV results for the direct effect: CO_2 cost (policy scenario - zero+ alternative)

Appendix F

The final sensitivity analysis performed is towards the adjustments of multiple variables at the same time. In chapter 6, the tornado sensitivity figures are shown for the Western route, in Appendix F the tornado sensitivity analysis for all three routes are visualized. In this analysis the eight most influencing variables have been tested. Combinations have been made in which the influence is expected to be the most.

Western route

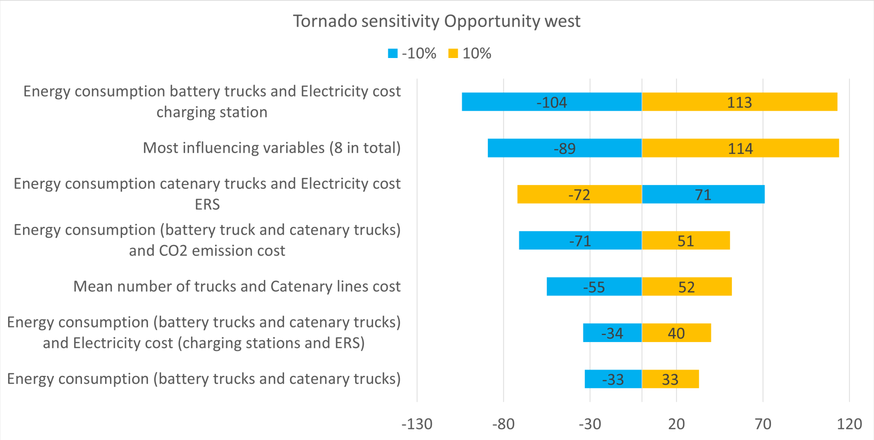

Figure 8.16: Sensitivity analysis NPV results variables combined: policy scenario - zero alternative with opportunity charging

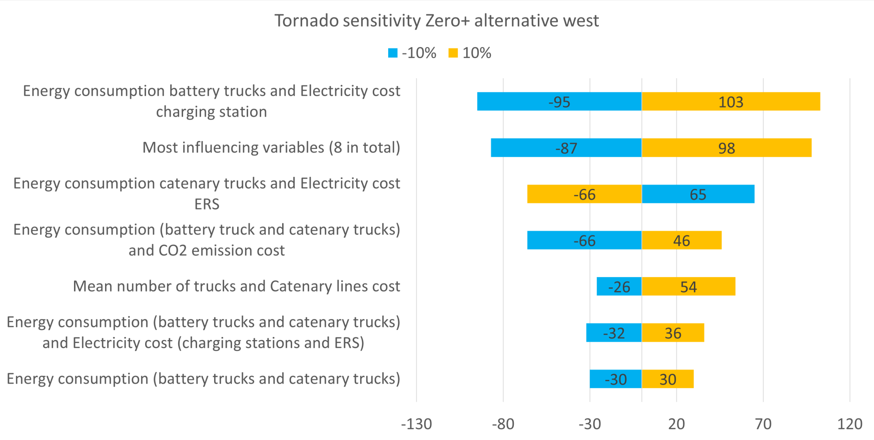

Figure 8.17: Sensitivity analysis NPV results variables combined: policy scenario - zero+ alternative

Middle route

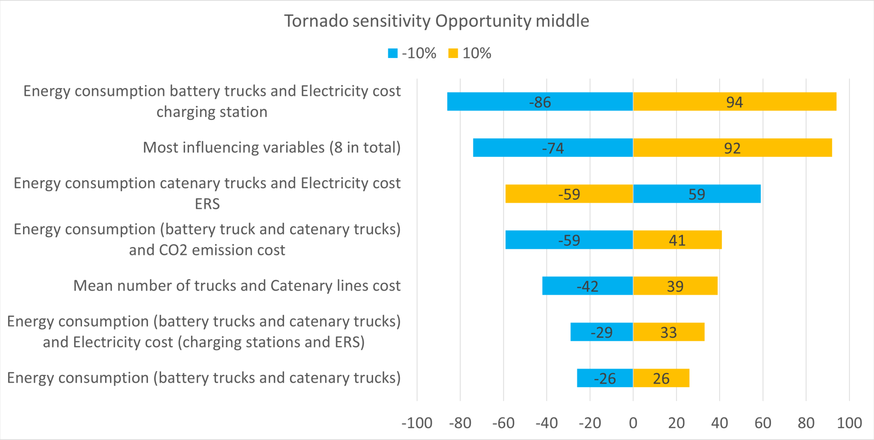

Figure 8.18: Sensitivity analysis NPV results variables combined: policy scenario - zero alternative with opportunity charging

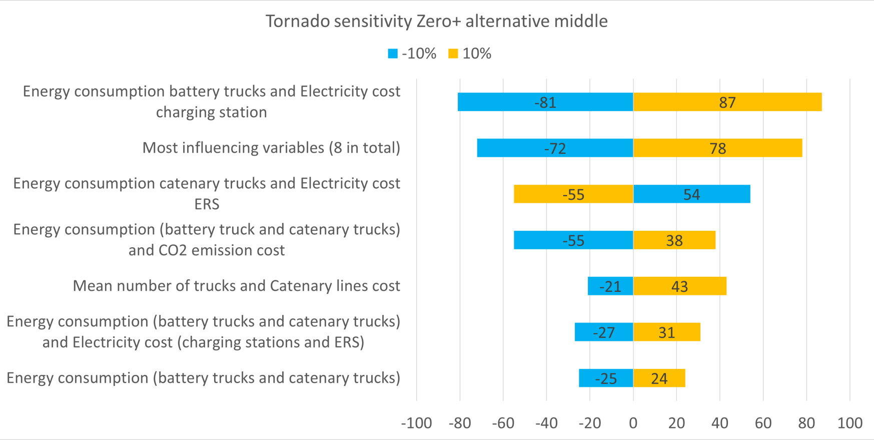

Figure 8.19: Sensitivity analysis NPV results variables combined: policy scenario - zero+ alternative

Eastern route

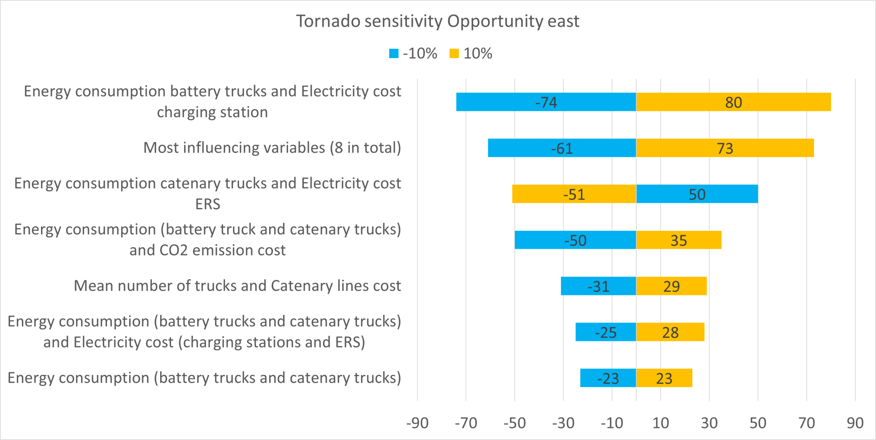

Figure 8.20: Sensitivity analysis NPV results variables combined: policy scenario - zero alternative with opportunity charging

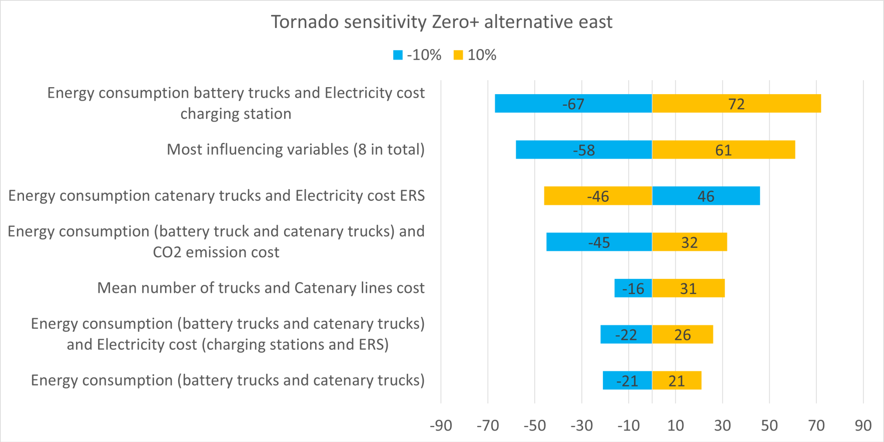

Figure 8.21: Sensitivity analysis NPV results variables combined: policy scenario - zero+ alternative