Strategies for decarbonization of heavy-duty road freight

Social-economic feasibility study on the hinterland of the port of Rotterdam

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TU Delft

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Strategies for decarbonization of heavy-duty road freight

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

This master thesis is the result of a graduation research work that comprised a multidisciplinary project of 21 weeks linked to the track Transport & Logistics of the Master Complex Systems Engineering and Management at the TU Delft. The Port of Rotterdam offered me a graduation internship at the Strategy and Analysis department for the execution of this research project. The research will be continued by a PhD student of the TU Delft from 2023 – 2027.

The thesis is about decarbonization of the heavy-duty freight, which should happen to meet the climate target in 2050. I think the thesis provides insights into an objective manner that could make a contribution to sustainable road freight in the future. There are many supporters that 'believe' different energy carriers could offer a solution for decarbonization of heavy-duty freight. I think these beliefs are good to some extent. Just like the song of DI-RECT says; "Who wants to live forever, when there is nothing to believe in?" However, to meet the academic standards, I tried to make the feasibility study as objective as possible, leaving the beliefs out of scope.

For the realization of this report I would like to thank my Graduation Committee. First, I would like to thank my first supervisor, Jan Anne Annema, for giving valuable feedback many times, especially on the social-cost benefit analysis and the structure of my report, also thanks for the many sparring sessions. I think both certainly contributed to a better final research report. For planning the milestone-points well in advance and further feedback, I would like to thank Lydia Stougie. This definitely helped me to stay on track with my schedule. For many informative resources, events and the opportunity to collaborate with public and private parties in the transport sector, I would like to thank Lóri Tavasszy. In addition, I would like to thank Pieter de Waard, mainly for his financial insights, but also for making my first work experience at the Port of Rotterdam lots of fun. Last, I would like to thank my family for all their support, always.

The finishing of my master thesis project at the TU Delft and my graduation internship at the Port of Rotterdam marks the end of my academic career. These six years I developed myself by gaining knowledge and skills at the TU Delft and learning from the side-curriculum activities; competitive rowing, ROTC-sailing, dream team year at AeroDelft, start-up STAND, a semester abroad in Madrid and living with co-students in Huize Sagrada Familia. I am thankful for all the opportunities that the TU Delft gave me. With all I have gained at the TU Delft I aim to make a contribution to society in the future.

Janske Otten.

Delft. July 2023

Executive summary

Heavy-duty road transport needs to make a transition to become climate neutral in 2050 (Plötz et al., 2023). Road transport causes 40 % the CO_2 emissions of hinterland transport, while road transport does not cover the longest distances. Not considering the negative impact on the environment, road transport remains a competitive way of transportation in the hinterland of maritime ports (Lechtenböhmer et al., 2018). Policymakers of the European Union, Dutch government and strategists of the Port Authority Rotterdam already proposed or even implemented interventions to enable the transition in the heavy-duty segment from fossil fuels to alternative energy carriers. However, they provide an unclear direction considering energy carriers by stimulating both electricity and hydrogen as energy carriers. This results in the following problem statement: *Policymakers and strategists of the Port Authority have a lack of knowledge to decarbonize heavy-duty transportation in the hinterland, without deteriorating the competitive position of a maritime port as a transit node.*

This practical problem is also discussed in the scientific literature. Various studies are made about the transition in the heavy-duty road segment. However, the following knowledge gap is identified in the literature: *A social cost-benefit analysis that assesses social-economic welfare effects of energy carriers to decarbonize heavy-duty road transport in the hinterland of maritime ports remains unaddressed in the literature.*

The research objective is to investigate the socio-economic feasibility of the strategies for decarbonization of heavy-duty road transport in the hinterland of maritime ports. The objective is to find a more clear direction considering the alternative energy carrier. Accordingly, the main research question is defined: *What is the socio-economic feasibility of strategies for decarbonization of heavy-duty road freight transport in the hinterland of maritime ports towards 2050?*

The socio-economic feasibility of the strategies can be compared by making a social-cost benefits analysis (SCBA). This method is chosen as the main approach since the results of the analysis show which strategy would be most welfare enhancing (Mouter, 2021). It is therefore desirable for the policymakers and strategists to rely on this socio-economic welfare perspective that covers both public and private values. The SCBA provides information in an objective manner (Mouter, 2012). This objective information supports policymakers and strategists for making deliberate decisions for infrastructure investments. If financial support of the Dutch government is required, it is also obligated to make a cost-benefit analysis (Wiegmans et al., 2022). The scope of the SCBA is the Rotterdam – Duisburg corridor, since most freight is transported to Germany (CBS, 2018). The time horizon of the analysis is set from 2023 to 2050, in line with the climate targets stated in Plötz et al. (2023).

Prior to the SCBA, a literature was executed to find what are promising energy carriers to decarbonize heavy-duty freight. Battery electric vehicles (BEVs) that use renewable electricity were found to be promising, since they are energy efficient due to their few conversion processes in the drivetrain. This results in a lower energy demand compared to other energy carriers (Cunanan et al., 2021). Besides, the production process of renewable electricity requires less conversion processes. Furthermore, the total cost of ownership (TCO), which comprises the purchase and the usage costs of BEVs is expected to decrease, resulting in a more competitive way of transportation (Tol et al., 2023). A catenary electric road system (CERS) could supply more direct electricity, and thereby enhance the performance of the batteries. This reduces the peak load on the grid, lowers the purchase costs of BEVs and reduces difficulties with recharging time and limited battery range (Bateman et al., 2018; Ainalis et al., 2020). The fuel cell electric vehicles (FCEVs) that use green gaseous hydrogen as energy carrier, are also perceived as promising. Mainly because their range is expected to exceed the range of the BEVs and the refueling time also remains shorter than the ones of BEVs. These would be important factors for long-haul transportation (Cunanan et al., 2021; Tol et al., 2023)). Lastly, e-diesel is found to be promising as an energy carrier. Since e-diesel can be used in the internal combustion engine of a conventional heavy-duty vehicle. Thus, the current fleet and the existing infrastructure could also still be used (Prussi et al., 2022). The tariffs for both hydrogen and e-diesel might be lower in port areas since the production of these energy carriers could take place there. All three energy carriers have the potential to meet the zero-emission climate targets (Tol et al., 2022; Tol et al., 2023; Van Kranenburg, 2020). In figure 1, the expected development of the TCO and the availability of the energy carrier, technology and infrastructure are put in a timeline.

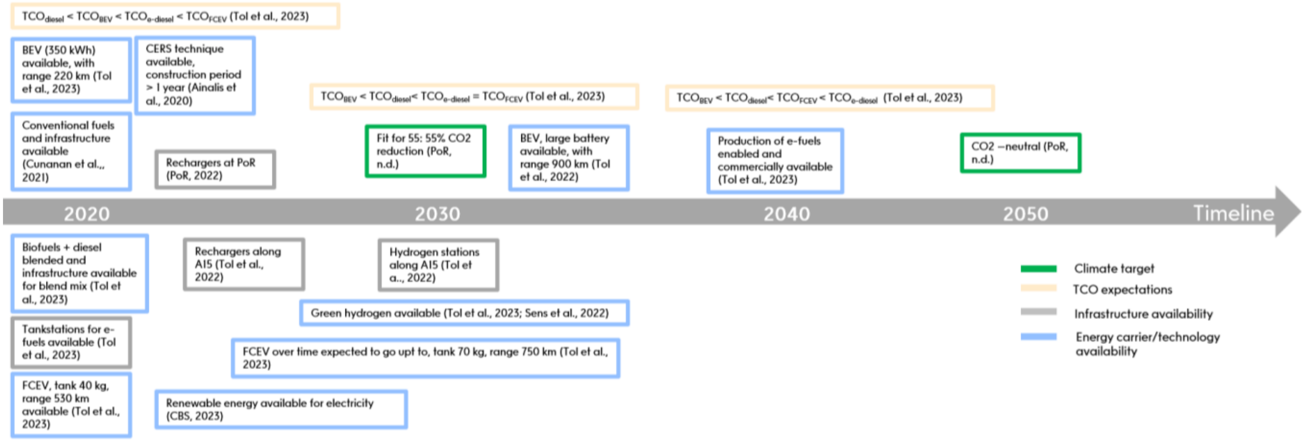

Figure 1. Timeline of TCO and the availability of energy carriers and technologies

The strategies proposed in this thesis were developed based on the availability of promising energy carriers and technologies to decarbonize heavy-duty freight. A technology or energy carrier is only stimulated or obligated in the strategy if it is available. Furthermore, the subsidy for the zero-emission technology is only provided if the $TCO_{\text{zero-emission technology}} < TCO_{\text{fossil fuel based technology}}$. Otherwise, through market forces the subsidy would not be necessary. The strategies are presented in figure 2. The same literature review is also used to find out what the forecasts are of developments of the heavy-duty fleet and infrastructure considering energy carriers and technologies if no interventions are taken. Subsequently, the zero-alternative is defined based on the forecasts if no interventions are taken and is also shown in figure 2.

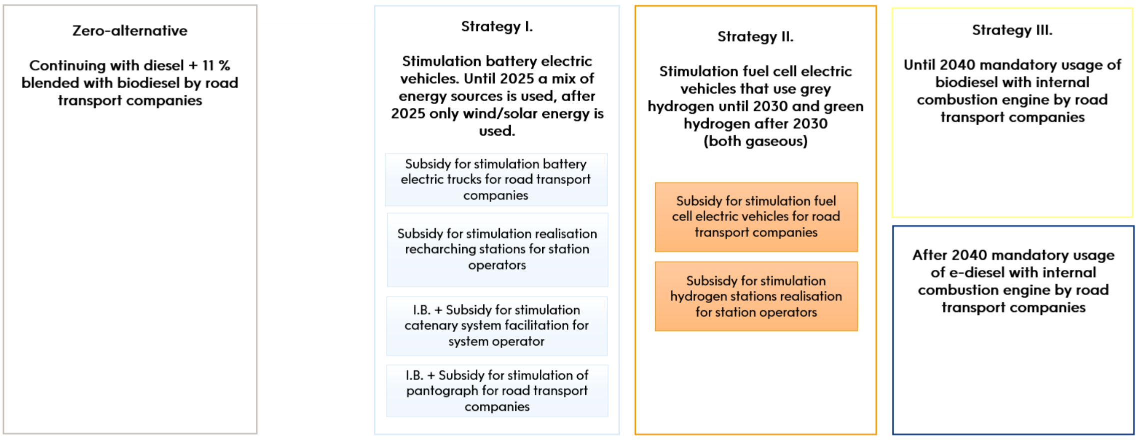

Figure 2. Zero-alternative and strategies

Based on an additional literature review and analytical thinking, the social-costs and the benefits that are included in the SCBA are conceptually identified and categorized in four different groups:

1. The direct effects, consisting of benefits for the road transport companies and station operators that due to the subsidies can afford alternative technologies (in jargon: their producer-surplus increases);
2. The external effects, these are considered from the production to the usage phase of the energy carrier (e.g. less CO_2 emissions);
3. The indirect effects, consisting of fuel tax losses;
4. The societal costs, consisting of the subsidy.

Only costs and benefits are included if there is a difference distinguished between the strategies and the zero-alternative. If the costs and/or benefits take place in different years they are discounted with 2.25 %. This rate is based on the guidelines of the Ministry of Finance (2020). Corresponding formulas are made for the costs and benefits, data is collected for the input variables and the SCBA is made in line with the guidelines for the SCBA of the Dutch government stated in Renes and Romijn (2012).

The results in table 1 show per strategy the invested subsidy, the CO_2-reduction compared to the zero-alternative and the Net Present Value (the balance of the costs and the benefits from 2023 to 2025). The results can be used to compare the socio-economic feasibility of the strategies.

Table 1. Final results of the social cost-benefit analysis.

	I.A. Stimulation battery electric vehicles	**I. B. Stimulation battery electric vehicles + catenary electric road system**	**II. Stimulation fuel cell electric vehicles**	**III. Mandatory biofuels until 2040 and after e-diesel**
Invested with subsidy [euro]	**-418,000,000**	**-1,007,000,000**	**-672,000,000**	**0**
CO_2-reduction in 2050 compared to zero-alternative [%]	**- 50**	**- 50**	**- 30**	**- 35**
Net Present Value [euro]	**-401,000,000**	**-696,000,000**	**-431,000,000**	**-671,000,000**

Considering the socio-economic feasibility, the negative net present values show that all proposed strategies are not welfare enhancing and thus unfeasible from a socio-economic perspective. This means that for all strategies the benefits do not outweigh the costs, even with the environmental benefits included. The negative net present values are mainly caused by the severe losses of tax on fossil fuels. The strategies show a CO_2-reduction between 30 – 50 % compared to the continuation with conventional fuels. However, the climate target of 100 % CO_2-reduction is not achieved in one of the strategies.

It can be concluded that the strategy in which BEVs are stimulated by subsidy are the most feasible from a socio-welfare perspective. The environmental benefits are the highest due to the early availability of renewable electricity and the subsidy is the lowest due to the lowest purchase price compared to other zero-emission vehicles. It can also be concluded that strategy II stimulates the purchase of fuel cell electric vehicles too early in 2025. Green hydrogen will only be available after 2030, Therefore, between 2025 and 2030 there will be a peak in carbon emissions caused by the usage of grey hydrogen in the fuel cell electric vehicles. This results in an overall cost for the carbon-emissions from 2023 to 2050. It also means the Net Present Value of strategy II becomes even more negative, when the environmental prices for emitted CO_2-emissions rise.

The uncertainty analysis showed that the strategy in which BEVs are stimulated by subsidy would be welfare enhancing if the CO_2-valuation would be increased up to 500 euro per kg, as shown in figure 3. The strategy in which the catenary electric road is subsidized is perceived as the second welfare enhancing option if the CO_2-valuation is increased.

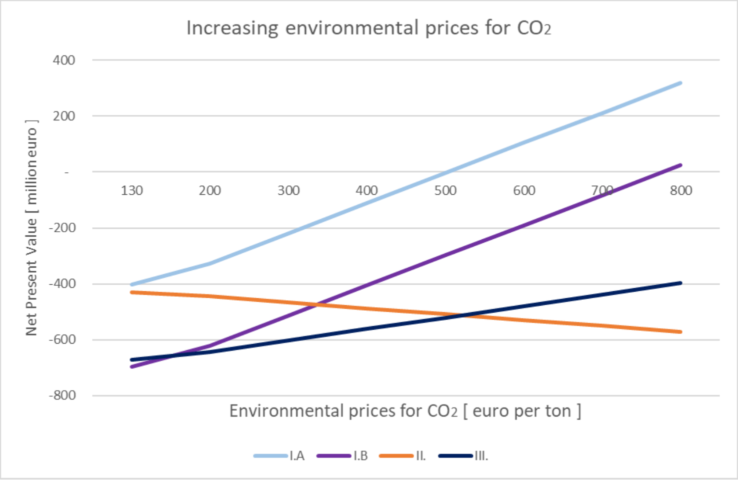

Figure 3. Change in NPV by increasing CO_2-prices

The recommendations to the Dutch government and the Port Authority are to align their policy and strategy to provide a more clear direction considering energy carriers and technologies. It is important that the infrastructure in the hinterland is aligned with the infrastructure in port areas to avoid sunk costs. It is also important for a port in order to remain competitive as a transit node. Besides, the current policies are tank-to-wheel based for the polluted emissions, while it would be desirable to make the policies well-to-wheel based in order to consider the emissions of the entire chain. The production process of an energy carrier could cause a high level of emissions. In that case, it would be undesirable to promote the energy carrier in a policy. In addition, the Dutch government is recommended to monitor the high expenditures for subsidies and the severe losses of tax on fossil fuels. This combination might be unaffordable for the government. Last, it is advised to make zero-emission heavy-duty vehicles mandatory. Since without obligation, the climate targets will not be achieved.

The study knows several limitations. These limitations are discussed and subsequently recommendations for further research are made. The study considers only the Rotterdam – Duisburg corridor. It would be recommendable to consider the entire European network, since road transport is mainly organized continental (Pastowski, 2017). Another limitation is that most of the costs and benefits are considered from the refueling and usage part phase (the tank-to-wheel scope). However, it could be that the production, distribution and conditioning of the energy carrier also have high expenditures (Prussi et al., 2022). Therefore, it is recommendable to also investigate these costs and benefits. Last, another limitation is that by the use of the SCBA, the technical feasibility is disregarded. This could cause potential barriers in the future. For example, the grid capacity for recharging BEVs (Tol et al., 2023). It would be interesting to do further research on the technical feasibility of the identified potential barriers.

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List of abbreviations

AFIR – Alternative Fuel Infrastructure Regulation

BEV – Battery Electric Vehicle

CERS – Catenary Electric Road System

CNG – Compressed Natural Gas

CO_2 – Carbon dioxide

DME – Dimethyl-ether

e-fuel – electro-fuel, also known as synthetic fuel

ERS – Electric Road System

FCEV – Fuel Cell Electric Vehicle

GVW – Gross Vehicle Weight (includes the weight of the vehicle and the cargo)

H_2 – Hydrogen

HDV – Heavy-duty vehicle

ICEV – internal combustion engine vehicle

kWh – kilowatt hour

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

MVA – Mega Volt Ampère

MJ – Mega Joule

Mt – Megaton

NH_3 – ammonia

NO_x – Nitrogen Oxides

PoR – Port of Rotterdam (this is the Port Authority not the port area in Rotterdam)

PM_{10} – Particles smaller than ten micrometers, also known as particulate matter.

PM_{sl} - PM_{10} emissions from wear

PM_v – PM_{10} emissions from combustion

SCBA – Social cost-benefit analysis

SO_2 - Sulfur dioxide

TCO – Total Cost of Ownership

tkm - ton-kilometer

TTW – Tank-to-wheel

TWh - Tera-Watt hour

WTT – Wheel-to-tank

WTW – Wheel-to-wheel

ze – zero-emission

Translation list

This translation list is included to provide a better understanding of some ‘Dutch concepts’ used in the study.

Articulated truck - vrachtwagen met aanhanger

Excise (duty) – Accijn (plicht)

Ministry of Economic Affairs and Climate - Ministerie van Economische Zaken en Klimaat

Ministry of General Affairs – Ministerie van Algemene Zaken

Ministry of Infrastructure and Water Management – Ministerie van Infrastructuur en Waterstaat

Netherlands Enterprise Agency – Rijksondernemend Nederland

Port Authority Rotterdam – Havenautoriteit Rotterdam, ook bekend als Havenbedrijf Rotterdam

Road transport company – wegvervoer bedrijf

Rigid truck – vrachtwagen

Tractor-trailer - trekker oplegger

Tax Authority - Belastingdienst

1. Introduction

In this chapter the societal problem and the knowledge gap are introduced. After, the research objective and questions are provided. There is also an explanation given for the choice and scope of the social-cost benefit analysis. Last, the link to the master program and structure of the thesis are provided.

1.1 Problem definition

In order to comply with the Fit for 55-proposal and the Paris Climate Agreement, the heavy-duty vehicles segment needs to reduce 55 to 67 % of its CO_2-emission by 2030 compared to the 2019/2020 levels and needs to be climate neutral in 2050 (Plötz et al., 2023). Currently, road transport in the hinterland of the port of Rotterdam is responsible for 0.9 Mt CO_2 emissions per year. The corresponding share of energy demand is 3.4 TWh, which is 41% of the total energy demand for hinterland transportation. These numbers include empty back transports. Road transport has the least sustainable emission factor with 1186 g CO_2 per km of the hinterland transport modes considering rail and inland shipping (Lechtenböhmer et al., 2018; Klein et al., 2020). 40% of the total CO_2 emissions of hinterland transport are caused by road transport, while road transport does not cover the most kilometers (Lechtenböhmer et al., 2018). Besides, road capacity remains a scarce resource. On the other hand, modal shift is not always possible due to the specific characteristics of the markets that the modalities serve. Therefore, the modalities are not completely interchangeable. In addition, optimization and alignment of schedules by using digital applications resulted in more operational and technological efficiency in logistic chains (Port of Rotterdam, n.d. -a), but more impactful changes need to be made to achieve the climate targets.

A port serves as a hub between maritime freight and hinterland freight transport. It also needs to supply the energy used by all modes relevant for port operations (Pastowski, 2017). The industrial cluster in the Rotterdam port area currently trades, handles, converts and uses fossil fuels. To decarbonize the industrial cluster two pathways are developed by the Wuppertal Institute on behalf of the Port Authority Rotterdam. These pathways could contribute to achieve the set climate targets. One pathway is the 'biomass and carbon capture storage-pathway,' in which a large demand and supply of biomass is expected and synthetic fuels have an important role. The other pathway is called 'closed carbon cycle,' in which renewables based electricity to supply heat and hydrogen plays an important role (Samadi et al., 2017; Samadi et al., 2018). The pathway also known as strategy applied by the Port Authority, could affect the prices of the decarbonized energy supply enabled by the industrial cluster. Likewise, the demand for certain energy affects the way the transition is enabled in maritime ports according to Samadi et al. (2018). This could also be relevant for the decarbonization strategy on the energy carriers used by heavy-duty road transport in the hinterland of maritime ports. A large demand by road freight for a specific energy carrier could affect the direction taken by the industrial cluster of the port of Rotterdam.

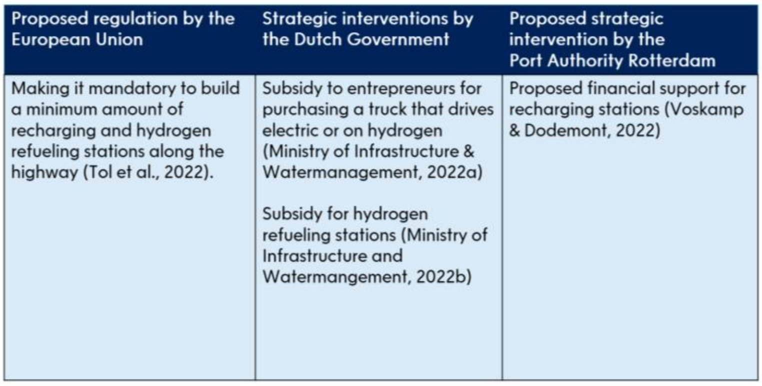
In addition, the strategy of the Port Authority also affects the infrastructure suitable for the energy carrier that is realized in port areas. Besides, it is also important that the infrastructure for road transport within port areas is aligned with the infrastructure in the hinterland. To ensure accessibility from the port to all relevant connections in order to remain its competitive position. High investments need to be made in infrastructure with a high level of uncertainty, potential sunk costs and the concern that there is a facilitated infrastructure, but no users or vice versa. Moreover, the transition cannot be organized centrally, since the road transport sector is fragmented as shown in the Transport Guide Rotterdam (n.d.).

Road transport in the hinterland mainly covers relatively short distances in continental areas and accounts for 106 Mt freight volume per year, which is 36% of the total freight volume towards the hinterland. In most scenarios the demand for road transport is expected to increase (Lechtenböhmer et al., 2018). For maritime ports road transport remains a competitive way of transportation, not regarding the negative impact on the environment. Thus, in order for maritime ports to stay competitive considering transportation to the hinterland, it is important that road transport remains reliable, profitable and accessible. These values could be conflicting with sustainability, when making the transition from fossil fuels to alternative energy carriers.

1.2 Practical problem statement and scientific knowledge gap

Currently, policymakers of the European and Dutch government and strategists of the Port Authority Rotterdam are trying to take an active role to enable this transition from fossil fuels to alternative energy carriers. Only relevant knowledge remains limited. An unclear direction considering the policy and strategy for the decarbonization of heavy-duty freight is given. The proposed regulations and strategic interventions are shown in table 2.

Table 2. (Proposed) regulation and strategic interventions by the European Union, the Dutch government and Port Authority



Proposed regulation by the European Union	Strategic interventions by the Dutch Government	Proposed strategic intervention by the Port Authority Rotterdam
Making it mandatory to build a minimum amount of recharging and hydrogen refueling stations along the highway (Tol et al., 2022).	Subsidy to entrepreneurs for purchasing a truck that drives electric or on hydrogen (Ministry of Infrastructure & Watermanagement, 2022a) Subsidy for hydrogen refueling stations (Ministry of Infrastructure and Watermangement, 2022b)	Proposed financial support for recharging stations (Voskamp & Dodemont, 2022)

The European Union proposed a new regulation, the Alternative Fuel Infrastructure Regulation, which demands to build a minimum amount of recharging and hydrogen refueling stations along the highway (Tol et al., 2022). The Dutch government provides a subsidy to entrepreneurs from 9 May 2022 when purchasing a truck that drives cleanly, either electric or hydrogen (Ministry of Infrastructure and Water Management, 2022b). In addition, an extra subsidy of 22 million is allocated for hydrogen stations with associated trucks (Ministry of Infrastructure and Water Management, 2022a). The Port Authority of Rotterdam made proposals for financial support of a recharging facility in the port area of Rotterdam (Voskamp & Dodemont, 2022). This results in the following practical problem statement: *Policymakers and strategists of the Port Authority have a lack of knowledge to decarbonize heavy-duty transportation in the hinterland, without deteriorating the competitive position of a maritime port as a transit node.*

This practical problem is scientifically also interesting. Several transition studies are made about the decarbonization of heavy-duty road transport. These studies are also relevant for the decarbonization of the road freight in the hinterland of maritime ports, since this mainly covers heavy-duty road freight (GeoWeb 5.5., n.d.). These transition studies are often qualitative in nature. Several decarbonization options, which are mainly alternative energy carriers and technologies, are reviewed on criteria like total cost of ownership, emission reduction and system integration readiness. Based on an assessment of these identified criteria, conclusions about the potential of energy carriers and technologies to decarbonize heavy-duty transportation are drawn (Tol et al., 2023; Fabius et al., 2020; Cunanan et al., 2021; Prussi et al., 2022; Frank et al., 2022). More quantitative research in which the criteria are integrated with different levels of uncertainty throughout time and in which the most promising energy carriers and technologies are compared remains rarely addressed. The socio-economic feasibility of the energy carriers also remains unidentified in the literature. The following knowledge gap is identified: *A social cost-benefit analysis that assesses social-economic welfare effects of energy carriers and technologies to decarbonize heavy-duty road transport in the hinterland of maritime ports remains unaddressed in the literature.*

1.3 Research objective and questions

The research objective is to investigate the socio-economic feasibility of strategies for decarbonization of heavy-duty road freight transport in the hinterland of maritime ports. By making a social cost-benefit analysis, the socio-economic feasibility of strategies can be compared in which alternative promising energy carriers are stimulated by subsidy or in which usage of alternative promising energy carriers is obligated. The aim is to investigate which strategy with a clear direction considering energy carriers is desirable based on their socio-economic feasibility.

Subsequently, the main research question is defined: *What is the socio-economic feasibility of strategies for decarbonization of heavy-duty road freight transport in the hinterland of maritime ports towards 2050?*

To investigate the main question the following sub questions are defined:

1. What are promising energy carriers to decarbonize heavy-duty road freight?
2. What are the forecasts for the development of the heavy-duty vehicles fleet and infrastructure regarding promising energy carriers if no interventions are taken?
3. How would strategies look like to decarbonize heavy-duty road transportation based on the identified promising energy carriers?
4. What are conceptually the costs and the benefits per strategy that should be taken into consideration in the social cost-benefit analysis?
5. How do the social-costs and benefits develop if the decarbonization strategies for heavy-duty transport are followed?
6. Which variables have a high level of uncertainty and influence on the results of the social costs-benefit analysis?

1.4 Explanation for method and scope choice

The social-cost benefit analysis (SCBA) is chosen as a method for three reasons. The first reason is that the socio-economic feasibility of strategies to decarbonize heavy-duty road freight can be compared by this method. The results show which strategy would be the most welfare enhancing (Mouter, 2021). The socio-economic welfare perspective is chosen as a theoretical perspective by making the SCBA (Mouter, 2012). This perspective is chosen since it is plausible that the energy carrier that appears to be most promising for decarbonizing road freight from a theoretical socio-economic perspective becomes dominant in practice due to market forces over time. Therefore, the Port Authority and policymakers could rely on this socio-economic welfare perspective when making investments in infrastructure suitable for a specific energy carrier.
The second reason is that the SCBA provides objective information (Mouter, 2012). The Port Authority and policymakers gain several objective insights which are critical points for the socio-economic feasibility of energy carriers to decarbonize road transportation. The objective information given by the SCBA could make the implemented strategy and thereby the

investment decision for the infrastructure suitable for a specific energy carrier more deliberate. The third reason is that it is obligatory to evaluate suggested infrastructure investment in port areas by the use of a cost-benefit analysis if financial support by the Dutch government is requested (Wiegmans et al., 2022). Thus, the SCBA can be used if financial support would be requested by the Port Authority for the infrastructure suitable for alternative energy carriers to refuel or recharge heavy-duty vehicles.

There is briefly reflected on why other methods that are often used to evaluate transport policies/strategies are not chosen in this study. First, the Environmental Impact Assessment (EIA) could serve as an alternative method to the SCBA. For the EIA the environmental effects are determined based on causal relation between source of impacts (such as land use change by new infrastructure) and their environmental impact. After, it is described which measures are taken to minimize the assessed environmental impacts. Compared to the SCBA, the EIA puts more focus on the environmental consequences and mitigation measures of a project (Mouter, 2021). The SCBA is preferred over the EIA, since the SCBA takes a broader scope by taking the environmental consequences, but also the welfare consequences into consideration. The Multi-Criteria Analysis (MCA) could also be used to evaluate transport policies/strategies. In the MCA the proposed policies are assessed on the selected criteria with a chosen weight. Compared to the SCBA, the MCA offers less strict procedures considering the criteria that are selected and for weighing the criteria (Mouter, 2021). Since the selected and weighting procedures could be more arbitrary than the SCBA-procedures, the SBCA is chosen instead of the MCA.

For the SCBA case study the scope of the Rotterdam – Duisburg corridor is taken, as shown in figure 3. This corridor is considered because it has a starting point in the port of Rotterdam. A relatively high amount of goods are transported to Germany, 44% of the loaded goods of road freight to foreign destinations are transported to Germany according to CBS (2018). Thus, Duisburg would be a likely point as a destination for the transported goods. In addition, the A15 which is part of the Rotterdam – Duisburg corridor, is the most important highway to and from the port of Rotterdam (Port of Rotterdam, n.d.-b). Characteristics of the considered heavy-duty fleet, the distances and the amount of trips driven on the corridor can be found in appendix B.

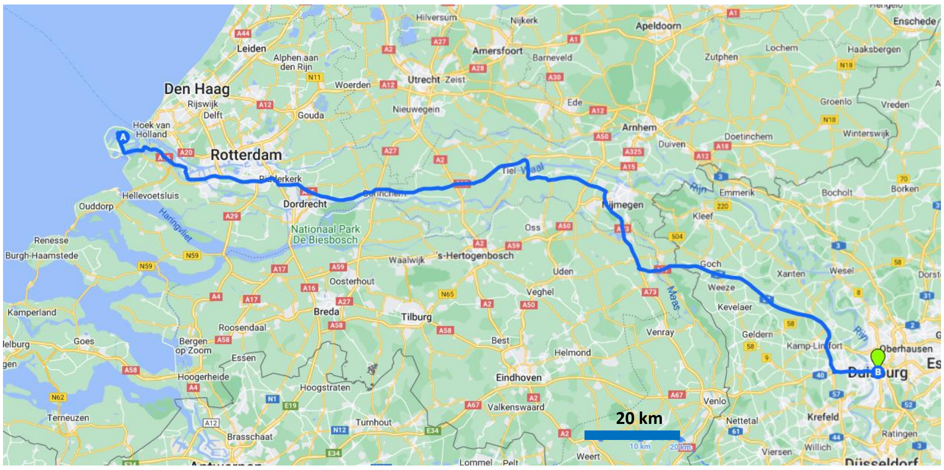


Figure 3. The Rotterdam – Duisburg corridor on scale 1 : 2 000 000

Note. Taken from Google Maps (n.d)
https://www.google.nl/maps/dir/Maasvlakte+Rotterdam/Duisburg,+Duitsland/

The time horizon regarded in the case study will be from 2023 until 2050, since most of the climate goals are set to 2050 according to Plötz et al. (2023).

1.5 Link to master program and structure of the thesis

In order to provide an answer to the sub questions and subsequently the main research question, a graduation research project is executed. The graduation research project comprises a multidisciplinary project of 21 weeks linked to the track Transport & Logistics of the Master Complex Systems Engineering and Management at the TU Delft. The project addresses a complex societal problem and covers values of both the public and the private domain. It includes system engineering-analysis about the embeddedness of the decarbonized road freight system in the hinterland of maritime ports and the development of the different energy carrier options in distinguished scenarios. It contributes to scientific knowledge about decarbonization in the hinterland of maritime ports and is also socially relevant by providing insights into the role that a maritime port can take to accelerate the transition in the hinterland.

The structure of this thesis is as follows. In chapter 2 the research method is discussed. In chapter 3, the findings of the first literature review are provided. Based on the additional literature review, the conceptualization of the costs and benefits are made in chapter 4. In chapter 5 the scope and core assumptions of the case study are defined. The results for the development of social-costs and benefits per the strategy are provided in chapter 6. The results of the uncertainty analysis are provided in chapter 7. Last, the discussion is given in chapter 8 and the main research question is answered in the conclusion stated in chapter 9.

2. Methods

In this chapter the methods are discussed. First, the main research approach is introduced in paragraph 2.1. After, the approach per sub question is discussed in paragraph 2.2 to 2.4.

2.1 Main approach

The main research approach used comprises a social cost-benefit analysis (SCBA) in a case study. A comparison between strategies can be made considering their socio-economic feasibility in a case study by making a SCBA. Strategies are made by the author in which promising decarbonization energy carriers are stimulated by subsidy or made obligated. The SCBA comprises all relevant welfare effects, improvements but also deteriorations of a project. The SCBA converts the results into one quantitative unit (Mouter, 2012). This final quantitative unit forms an indicator and is named the Net Present Value (NPV). If the NPV is positive the strategy is perceived to be welfare enhancing (Mouter, 2021). In this case the project is the strategy to decarbonize heavy-duty freight and the infrastructure that is proposed to be built in the strategy. The quantitative units per strategy compared in the case study show which strategy is most desirable considering their socio-economic feasibility. The strategy that appears desirable considering their socio-economic feasibility represents the interests of the society as a whole and thereby covers public and private values in an objective manner.

The SCBA has its origins in welfare theory and utilitarian way of thinking, this implies that the aim is to maximize utility and thereby welfare. A welfare improvement is defined as a change that does not make anyone worse off. This is the scientific definition of the pareto-improvement (de Boer et al., 2022). As a more practical definition it could be interpreted as follows; an improvement in welfare if the winners of a project can compensate the losers and there is still a net profit left.

2.2 Literature review for promising energy carriers and forecasts

In this paragraph 2.2 the sub method is provided for sub question I and II. For these two sub questions the same literature review is used. The literature review investigates what are promising energy carrier to decarbonize heavy-duty road transport (sub question I) and it investigates what the forecasts are for the development of the heavy-duty fleet and infrastructure regarding energy carriers in case no interventions are taken (sub question II). The method is shown in figure 4 and after it is further explained.

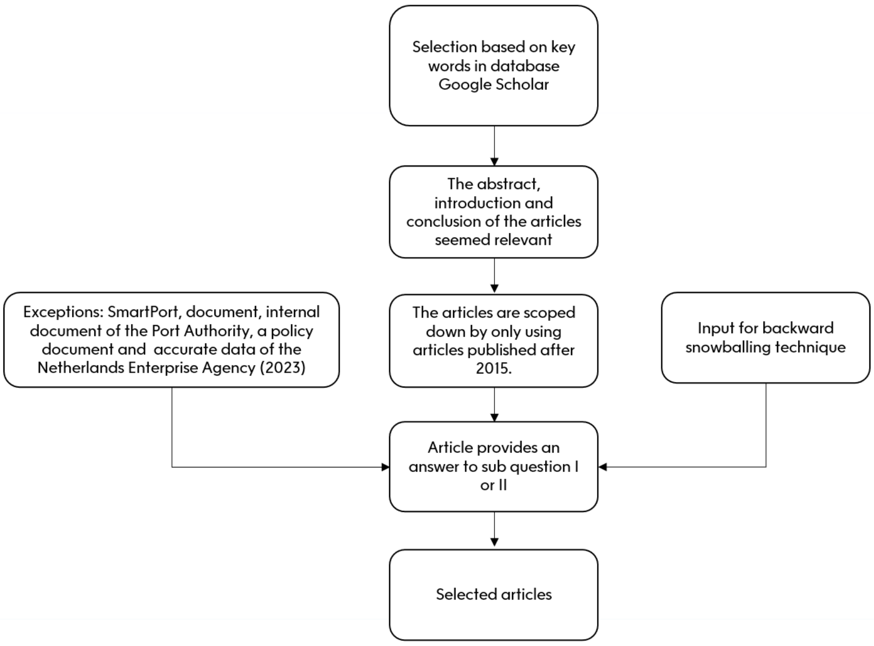


Figure 4. The literature review method for sub question I and II

In the literature review the articles are found by using the search engine Google Scholar. Keywords are used to find relevant articles of academic quality. The keywords are shown in table 3. The articles included in the literature review are shown in table 4. The articles are selected based on several factors. The abstract, introduction and conclusion of the articles seemed relevant for this literature review. After, the articles are scoped down by only using articles published after 2015. Last, the articles were only chosen if it provided a direct response to sub question one or two. The selected articles and their relevant discussed topic are shown in table 4.

Table 3. Keywords for sub questions I and II

Keywords for sub question I and II
(((heavy-duty AND vehicle) OR (heavy-duty AND truck) OR (heavy-duty AND transport) OR (powertrain AND technology) OR (road AND transport) OR (road AND freight) OR (hinterland AND transport AND maritime AND ports) OR (transport))
AND ((comparison) OR (advantages AND disadvantages) OR (impact AND assessment) OR (assessment))
AND ((decarbonization) OR (emission AND reduction) OR (renewable AND energy) OR (zero-carbon)))

In addition to the selection based on the keywords, backward snowballing-referencing method was used to find related studies to focus on distinctive concepts more in depth. Backward snowballing is a way of finding relevant literature by consulting the bibliography of an article (Jalali et al., 2012).

Besides the selection based on the key words and the backward snowballing-referencing a few other articles are included. The transition study of Fabius et al. (2020) on the topic of decarbonization of heavy-duty vehicles in the Netherlands is also taken into consideration. This study was commissioned by the Dutch Ministry of Infrastructure and Water Management and was made available online by the Dutch government. It is very plausible that the Dutch government bases its policy on this study. Therefore, the document of Fabius et al. (2020), which was found on the website of the Dutch government is also included in the literature review. A document of the Netherlands Enterprise Agency (2022) which is also made available on the website of the Dutch government, is also included. This article seemed relevant to assess the current and the past development of the heavy-duty fleet in the Netherlands, which was relevant for the forecasts. The papers of Tol et al., (2023) and Van Kranenburg et al. (2022) were found at an event and online of Knowledge Hub SmartPort. SmartPort organizes collaborations between port businesses, governments and knowledge institutions like the Erasmus University, the University of Technology Delft and TNO (Tol et al., 2023). The article of Tol et al. (2022), which made a study for the uptake of sustainable heavy-duty vehicles commissioned by the Port Authority Rotterdam was provided as an internal use document by the Port Authority and is also included.

In order to investigate what the forecasts are for the development of the heavy-duty fleet and infrastructure regarding energy carriers in case no interventions are taken (sub question II), the study of Cunanan et al. (2021), Tol et al. (2023), Bateman et al. (2018) are considered. These studies made forecasts on the uptake of the suitable infrastructure for sustainable energy carriers in the heavy-duty segment. The current fleet size is based on the data of the Netherlands Enterprise Agency (2022) and the study of Fabius et al. (2020). These studies made forecasts on the uptake of sustainable energy carriers in the Netherlands without strategic interventions. These sources appeared most applicable for the fleet in the Netherlands, since the Netherlands Enterprise Agency (2022) and Fabius et al. (2020), solely focus on the Netherlands. Based on these considered studies, the uptake of the heavy-duty fleet and the aligned infrastructure are assessed in case no interventions are taken.

Table 4. Topics discussed in articles relevant for sub question I and II

Author and year of publication	**Relevant topic discussed in text**							
	Used for sub question	Heavy-duty vehicles or road transport	Comparison or (advantages and disadvantages) or assessment	Powertrain (technology) or drivetrains or energy carrier or fuels	Decarbonization or emission reduction or zero-carbon or renewable energy	Hinterland (maritime port)	Forecast or expectation	Current fleet or current infrastructure
Ajanovic et al. (2021)	SQ1	■		■	■			
Ainalis, et al., (2020)	SQ1	■			■			
Bateman,, et al., (2018)	SQ1, SQ2	■		■				■
Bosteels et al., (2022)	SQ1	■		■	■			
Cunanan et al., (2021)	SQ1, SQ2	■	■	■	■			■
Dimitriou et al., (2020)	SQ1	■			■			
Fabius et al., (2020)	SQ1, SQ2	■			■		■	■
Frank et al., (2022)	SQ1	■	■		■			
Van Kranenburg et al. (2022)	SQ1	■		■	■			
Lechtenböhmer et al., (2018)	SQ1	■			■	■		
Panoutsou et al., (2021)	SQ1	■			■			
Parviziomran et al. (2023)	SQ1	■			■			
Pastowski, (2017)	SQ1	■		■	■	■		
Plötz (2022)	SQ1	■	■		■			
Plötz et al (2023)	SQ1	■	■		■			
Prussi et al., (2022)	SQ1	■	■	■	■			
Sen et al., (2017)	SQ1	■		■				
Sens et al., (2022)	SQ1	■	■					
The Netherlands Enterprise	SQ2	■						■

Agency (2022)		■						■
Tol et al., (2022)	SQ1, SQ2	■		▒	■	■		
Tol et al., (2023)	SQ1, SQ2	■		▒	▒			▒

2.3 Method for made strategies to decarbonize heavy-duty freight

Subsequently, the zero-alternative and the strategies are made by the author for a case study to answer sub question three. Both are thus made for the heavy-duty fleet that drives on the Rotterdam – Duisburg corridor. The zero-alternative and strategies are made in line with the guidelines of the manual for social cost-benefit studies by Renes and Romijn (2013). The guideline is made available by the Dutch government. The zero-alternative is based on the most likely development in case no policy interventions take place to alter the current situation (Renes & Romijn, 2013), for which the answer to sub question two is mainly taken into account. Since in the forecasts found in sub question II no interventions are taken. The alternative strategies are aligned with the most promising energy carriers based on the literature review. Thus, indirectly all articles mentioned in table 4 are used for making the strategies and thus answering sub question III. Thus, the strategies are made consistent with the findings of the literature review.

For making the strategies, the articles of CBS (2023) and Klein et al. (2020) are also considered to find the availability of renewable energy in the Netherlands that is used by the ze-vehicles. These sources are found to be more applicable to the fleet that drives on the corridor Rotterdam – Duisburg since it focuses on the renewable energy supply in the Netherlands. The policy documents of the Ministry of Economic Affairs and Climate (2019), the Tax Authority (2023) and Rijkswaterstaat (2021) were also taken into consideration to ensure that the strategies comply with the Dutch regulation. These (policy) documents are found on the website of the Dutch government (rijksoverheid.nl) or websites of other governmental institutions (de Belastingdienst and the Centraal Bureau voor de Statistiek). The report of Klein et al. (2020) is found on the website of CE Delft.

In the strategies, two policy instruments are used: stimulation by subsidy and obligation by legislation. Both instruments can be used by the Dutch government in collaboration with the Port Authority. For the strategies, purchasing zero-emission vehicles are stimulated or obligated and possible adaptations to the environment in forms of new infrastructure suitable for sustainable energy carriers are stimulated or obligated.

The possible adaptations to the environment are based on the proposed European regulation stated in Tol et al., (2022). This European regulation makes it obligatory to build infrastructure that needs to be built in order to support the use of the zero-emission vehicles. It could also be that the infrastructure already is in place to a large extent. Personal communication with private company FastNed took place to find out if stations were already suitable to welcome heavy-duty vehicles. These facts are also considered in the strategies.

In the alternative strategies, the level of subsidy for the zero-emission vehicles given to the transport road transport companies are defined based on the difference between the predicted purchase of the sustainable heavy-duty vehicle and the predicted purchase price of the conventional heavy-duty vehicle. Since the difference is covered by subsidies, it will become more attractive to buy a zero-emission vehicle. The subsidy for the infrastructure given to the station operators is based on the observed building costs and should cover around 50 % of it. The demand for the usage of the station is also already increased indirectly through the subsidy for the zero-emission vehicles. If there are more zero-emission vehicles it is likely that the stations that could provide energy for the zero-emission vehicles are used more often. The demand of the energy carrier is thus increased indirectly. Since the station operator thus also benefits from the subsidy for the zero-emission vehicles indirectly, only half of the building costs of the infrastructure are covered and not the full costs.

2.4 Additional literature review for costs and benefits included in the SCBA

It is determined which costs and which benefits should be taken into consideration in the social-cost and benefit analysis. This is first done conceptually. For the identification of the costs and benefits an additional literature review is executed. Own analytical thinking also partly determines which costs and benefits are included in the SCBA. Both provide an answer to sub question IV. It is first identified which effects and costs a measure has and after that it is checked if it is relevant to include in the SCBA on the basis of welfare economic principles. This procedure is in line with the guidelines of Renes & Romijn (2013). Only the benefits and the cost that differ from the zero-alternative are relevant. It is about the difference, the delta, between the strategies and the zero-alternative perceived (Renes & Romijn, 2013). The costs or benefits of a strategy are thus only included if there are resources required to implement and maintain a strategy which were not required in the reference case. For the conceptualization of the identified costs and benefits also corresponding formulas are made.

For the literature review the following method is applied. The relevant articles are found using the online TU Delft Library. The TU Delft Library is used since the TU Delft offers several courses in which the social cost-benefit analysis is discussed as a method. Therefore, it is plausible that relevant articles on the SCBA method are available in their online library. The keywords that are used to find relevant articles of academic quality are shown in table 5. The title, the abstract, introduction and conclusion of the articles seemed relevant for this literature review. The articles are scoped down by only using articles published after the 2010s. The articles were only included if the text provided a response to sub question four.

In addition to this selection based on keywords in the database of the TU Delft Library, the back-referencing method was used to find related studies to focus on distinctive concepts more in depth. In addition, the article of Annema et al. (2021) is found at a lecture of the TU Delft. The articles included in the additional literature review are shown in table 6 and thus appeared relevant for the determination of the costs and the benefits that are included.

Table 5. Keywords for sub question IV

Keywords used for sub question IV
(((CBA OR cost-benefit analysis OR SCBA OR social cost-benefit analysis))
AND (indicators OR effects)
AND ((heavy-duty AND vehicle) OR (heavy-duty AND truck) OR (heavy-duty AND transport) OR (powertrain AND technology) OR (road AND transport) OR (road AND freight))
AND ((transport AND projects) (infrastructure AND investment)))

Table 6. Topics discussed in articles relevant for cost and benefits

Author and year of publication	**Discussed topic in title or abstract or executive summary**			
	CBA	Effects	Transport projects	Heavy-duty vehicles
Annema et al., (2021)	▨		▨	
Mouter, (2014)	▨	▨	▨	
Mouter et al., (2019)	▨	▨	▨	
Wiegmans et al., (2022)	▨		▨	

2.5 Method for the social cost-benefit analysis

The development of the social-costs and benefits if the decarbonization strategies for heavy-duty transport are followed, are shown in the results of the social cost-benefit analysis. These results provide an answer to sub question V. The costs and benefits that were first conceptually defined with their corresponding formula through the additional literature review, are entered in the excel model.

The data that is required to enter into the formulas as an input variable is collected. The data is collected by (policy) documents available on Google Scholar and Google. In addition, internal information of the Port Authority of Rotterdam and personal communication with private company FastNed also forms an input for the data. For all data collected the source is stated in the appendices. If assumptions are made about the data, this is also mentioned the appendices. The scope of the SCBA case study is also elaborated on in chapter 5. The data has been entered in Excel as input variables and are indicated with a yellow color.

Subsequently, calculations are made in Excel based on the formulas that were stated in the conceptualization. The costs and benefits are calculated for each strategy to decarbonize heavy-duty transport. Since the costs and the benefits considered do not coincide at the same time, all the costs and benefits are calculated back to the same base year. These calculations are known as discounting. The idea behind discounting is that individuals prefer to receive an euro today over receiving a euro tomorrow. Since an euro can be put on the bank and plus interest it will become more. Discounting is done with a fixed percentage, also known as the discount factor (Renes & Romijn, 2012). The level of discount factor is based on a policy document of the Ministry of Finance (2020), which is made available on the website of the Dutch government.

In order to compare the strategies, the final indicators which are the Net Present Values and the cost-benefit ratio of each strategy are calculated in Excel. The formula of the Net Present Value (NPV) can be calculated according to Gaspars-Wieloch (2019) and the benefit-cost ratio according to the Corporate Finance Institute (2022):

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

With: CI [euro] is the cash inflow, thus the benefits in the SCBA,
CO [euro] is the cash outflow, thus the costs in the SCBA,
t is the time [years] with 2023 is year 1,
the discount factor = 1 / (1 + r) ^ (t – 1) in which r is the discount rate,
n is the number of periods, thus 2023 to 2050 is 28 periods.

Equation 1. Net Present Value (Gaspars-Wieloch, 2019)

:

ii.) Benefit-cost ratio = $$\frac{\sum_{t=0}^{n} \frac{CI_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{CO_t}{(1+r)^t}}$$

With: CI [euro] is cash inflow, thus either benefits or costs in the SCBA,
CO [euro] is the cash outflow, thus the costs in the SCBA,
t is the time [years] with 2023 is year 1,
discount factor = 1 / (1 + r) ^ (t – 1) in which r is the discount rate [ ],
n is the number of periods [ ] , thus 2023 to 2050 is 28 periods.

Equation 2. Benefit-cost ratio (Corporate Finance Institute, 2022)

2.6 Method for uncertainty and sensitivity-analysis

The uncertain analysis is made to investigate quantitative changes in the model that affect the final result shown in the Net Present Values. For the uncertainty analysis it is first investigated qualitatively if the factors have a high level of uncertainty and if the factors have a high level of influence. If the factors score high on both criteria there are taken into consideration in the uncertainty analysis as shown in figure 5. The level of uncertainty of the factors is based on the executed literature reviews and the level of influence on the extreme values shown in the results of the model. It is important to remark that the factors are only included if there is a difference between the zero-alternative and the strategies. Otherwise, the uncertainty cannot be investigated by a social cost-benefit analysis.

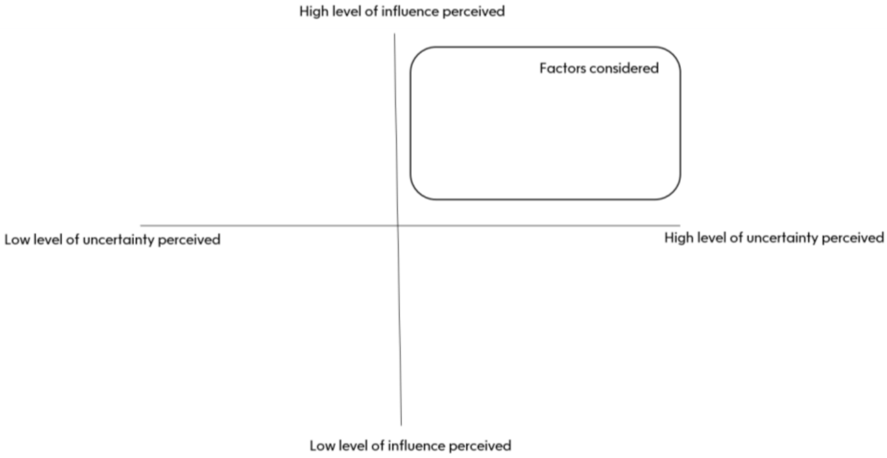


Figure 5. Graph for uncertainty analysis

After the qualitative analysis, the factors that have a high influence and a high level of uncertainty are quantitative addressed. By taking different values of these factors the influence on the Net Present Values of the strategies are investigated.

The influence of the input variables is also analysed by a sensitivity analysis. By the sensitivity analysis it is determined how sensitive the model is to changes of the input variables. All input variables are changed one by one, while the rest of the input variables are kept constant. The input variables are changed by – 10 % and + 10%. It is looked at what impact this change of the input variable has on the Net Present Value of each strategy.

3. Strategies aligned with promising energy carriers

Based on the findings of the literature review, in this chapter the most promising energy carriers are discussed in paragraph 3.1. This provides an answer to sub question I. In paragraph 3.2, the forecasts are given for the development of the heavy-duty vehicles fleet and infrastructure regarding energy carriers if no interventions are taken. This provides an answer to sub question II. In paragraph 3.3, the zero-alternative strategies to decarbonize heavy-duty freight are made. The zero-alternative is aligned with the forecasts and the strategies are aligned with the most promising energy identified in the literature review. The made strategies give an answer to sub question III.

3.1 Determination promising energy carriers to decarbonize heavy-duty road freight

Several research has been done about the decarbonization options for road freight transportation, in table 7 it is outlined which energy carriers are discussed in which articles. As shown in table 7, diesel, battery electric vehicles (BEVs) that use electricity and fuel cell electric vehicles (FCEVs) that use hydrogen are the most discussed energy carriers and technologies in the considered articles. This might imply that more knowledge is already developed on these energy carriers and technologies.

The comparison made between the energy carriers is based on the selected articles. In most considered papers various climate-neutral energy carriers are compared with conventional diesel on a set of distinguished criteria. In the considered papers different perspectives are taken, for example more economic or environmental. Different criteria are valued on a scale and also different scopes are included, for example well-to-tank or tank-to-wheel. The compliance with current and future policies and legislation, and strategies of relevant market parties like manufacturers considering energy carriers is also included (Cunanan et al., 2021; Tol et al., 2023; Prussi et al., 2022; Lechtenböhmer et al., 2018; Pastowski, 2017).

Table 7.Topics discussed in articles about energy carriers

Paper	**Energy carrier/technology stated in the article**							
	Diesel	BEV	FCEV	e-fuels	CERS	Biofuels	Natural gas	Ammonia
Ajanovic et al. (2021)	▨	▨	▨			▨		
Ainalis, et al. (2020)	▨	▨	▨	▨	▨	▨	▨	
Bateman,, et al. (2018)		▨			▨			
Bosteels, et al. (2022)	▨			▨				▨
Cunanan et al. (2021)	▨	▨	▨		▨	▨	▨	
Dimitriou et al. (2020)	▨		▨					▨
Fabius et al. (2020)	▨	▨	▨					
Frank et al. (2022)	▨	▨				▨		
Van Kranenburg et al. (2022)	▨	▨	▨	▨		▨		
Lechtenböhmer et al. (2018)	▨	▨	▨		▨	▨	▨	▨
Panoutsou et al. (2021)						▨		
Parviziomran et al. (2023)	▨	▨	▨		▨			
Pastowski, (2017)	▨	▨	▨	▨		▨	▨	▨
Plötz (2022)	▨	▨	▨					
Plötz et al. (2023)	▨	▨	▨					
Prussi et al. (2022)	▨	▨	▨	▨	▨		▨	
The Netherlands Enterprise Agency (2022)		▨	▨					
Sen et al. (2017)		▨					▨	
Sens et al. (2022)		▨	▨					
Tol et al. (2022)	▨	▨	▨					
Tol et al. (2023)	▨	▨	▨	▨	▨	▨	▨	▨

In appendix C the different energy carriers are extensively discussed regarding several factors and perspectives over time. The potential energy carriers that are included in the analysis are shown in figure 6. The main advantages and disadvantages of the energy carriers can be found in table 8. Based on the comparison between the energy carriers and corresponding technologies a conclusion is made which are the most promising due to their (potential) performance. These energy carriers will be taken into further consideration in this study.

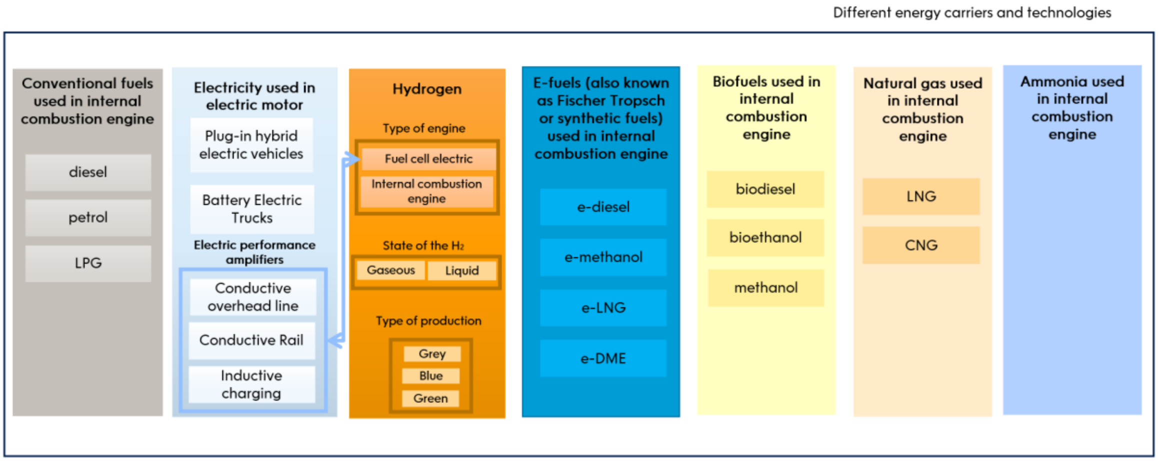


Figure 6. Overview of different energy carriers discussed

Note I: This figure is made based on all articles mentioned in table 7.

Note II: The arrow between the electric road systems and the fuel cell electric implies that these can also be used in combination. Thus, the hydrogen fuel cell electric vehicles can also make use of an electric road system as stated in Bateman et al. (2018).

Table 8. Advantages and disadvantages of energy carriers and technologies

Energy carrier and corresponding technology	Main advantage	Main disadvantage	References
Conventional fuels for in vehicles with internal combustion engine	+ Long range + Already existing infrastructure + Short refuelling time + Low vehicle purchase and usage costs.	- Climate targets not achieved	Cunanan et al., 2021
Electricity for in battery electric vehicles	+ Climate neutral if renewable energy is used + Energy efficient drivetrain + Energy efficient considering production process of electricity + Expected decreasing TCO + Low maintenance costs	- Currently short range and long recharging time for BEVs - Larger batteries reduce the payload capacity - Lack availability recharging facilities - Limited capacity on the electricity grid and potential net congestion - Limited availability raw materials for batteries	Cunanan et al., 2021 Plötz et al., 2023 Tol et al., 2023
Electricity for in battery electric vehicles in combination with	+ Reduce the peak load on the	- High investment costs for the	Bateman et al., 2018

catenary electric road system	grid + More direct electricity usage + Lower purchase costs for BEVs + Reduces the difficulties with recharging time and limited battery range + Increases charging convenience + High level of technological readiness	infrastructure - Investments in pantograph system are required - Initial low spatial coverage	Ainalis et al., 2020 Lechtenböhmer et al., 2018 Pastowski, 2017
Hydrogen for in fuel cell electric vehicles	+ Climate neutral if green hydrogen is used + Long range + Short refuelling time in FCEVs + Tariffs might be lower in maritime ports due to the proximity green electricity of off-shore wind	- Hydrogen tariffs are uncertain - Availability of green hydrogen is questionable - High safety risks - Lack of hydrogen refuelling stations - Distribution and conditioning near market facilities are not in place yet (H2- pipelines or tube trailers are necessary) - A purification system would also be necessary for the use of H2 in fuel cells - Lower TCO compared to BEVs	Plötz 2022 Sens et al. 2022 Ainalis et al., 2020 Cunanan et al., 2021 Tol et al., 2022 Tol et al., 2023
E-fuels for in vehicles with internal combustion engine	+ Potential to become climate neutral + Conventional vehicles with internal combustion engine and existing infrastructure can be used + Large range + Low safety risks + Tariffs might be lower in maritime ports, since the production can place in port areas	- Only commercially available after 2040 - Expensive production process required with many conversion steps - High energy demand for production process - Production process is not carbon-neutral	Prussi et al., 2022 Tol et al., 2023 Van Kranenburg., 2020
Biodiesel for in vehicles with internal combustion engine	+ Conventional vehicles with internal combustion engine can be used + Existing infrastructure can be use + Cost competitive with diesel + Large range	- Climate targets will not be achieved - Limited available to wide deployment	Ainalis et al., 2020 Tol et al., 2023
Natural gas for in vehicles with internal combustion engine	+ High level of technological readiness + Life-cycle environmental impact is perceived positive	- Climate targets will not be achieved - High safety concerns	Sen et al., 2017 Patowski et al. 2017

Ammonia for in vehicles with internal combustion engine	+ Only small adaptations in conventional vehicles needed	- Pollutes NOx - Risk of toxicity - Risk for explosion	Dimitriou and Javaid, 2020 Patowski et al. 2017

Concluding, the most promising energy carriers with corresponding technologies are shown in figure 7. All three energy carriers with corresponding technologies have promising potential emission reduction. The battery electric vehicles (BEVs) that use enewable electricity are promising mainly through their energy efficiency of the drivetrain and expected decrease in total cost of ownership (TCO). The TCO is a term used for the total cost during possession. It comprises all costs associated with purchasing, using and owning a vehicle over a period of time (Fabius et al., 2020). In addition, renewable electricity used in the BEVs requires the least conversion processes as shown in figure 8. The conductive overhead line could enhance the performance of the batteries and is therefore included in the further analysis. The range of the fuel cell electric vehicles (FCEVs) that use green hydrogen is expected to exceed the range of BEVs and the refueling time also remains shorter than the ones of BEVs. Therefore, the FCEVs would be promising for long-haul transport and are consequently perceived as promising. Last included is e-diesel, since the already existing infrastructure and vehicles could be used by this energy carrier. (Cunanan et al., 2021; Tol et al., 2023; Prussi et al., 2022; Lechtenböhmer et al., 2018; Pastowski, 2017).

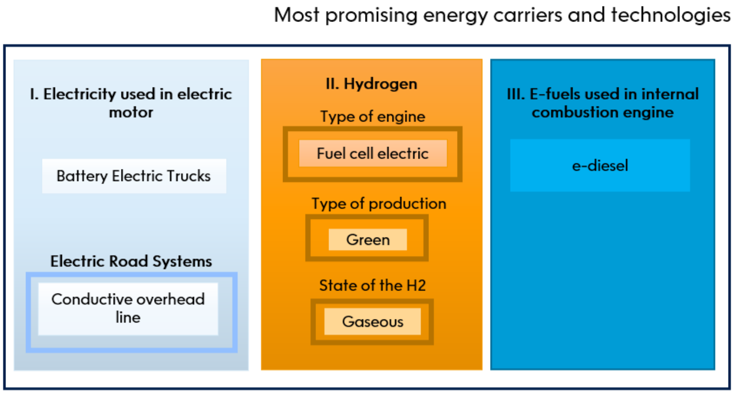


Figure 7. Most promising energy carriers and technologies based on literature review

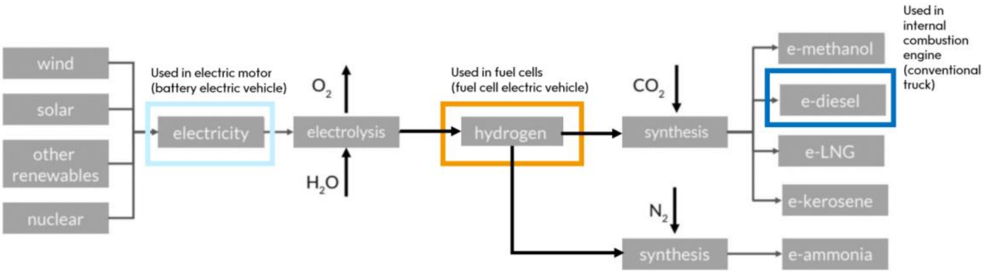


Figure 8. Production process energy carriers

Note I. Taken from “The potential of e-fuels for heavy-duty road transport in the Netherlands,” by Tol, D., Verbeek, M.M.J.F., Gaggar, S., Hulsbosch-Dam, C.E.C., Vredeveldt, A.W., van Zyl, P.S., van Ark E.J., Paschinger, P., Smokers, R.T.M. (2023). TNO, p.24, Available at Smartport.nl

Note II. The colored blue and yellow blocks are added based the statements of Tol et al. (2023).

3.2 Forecasts for the development of the heavy-duty vehicles fleet

The studies of Fabius et al. (2020) and Tol et al. (2023) determined the development of the heavy-duty fleet regarding type of energy carrier mainly on two factors. These factors are the forecasts of the availability of the energy carrier (the infrastructure, fuels and vehicles) and the Total Cost of Ownership (TCO) of the heavy-duty vehicles. If the TCO of a type of energy carrier is more attractive than the TCO of another type of energy carrier, it is more likely that heavy-duty vehicle suited for the type of energy carrier is purchased and used through market forces (Fabius et al., 2020; Tol et al., 2023). The blue line in figure 9 shows the forecasted uptake of fuel cell electric and battery electric heavy-duty vehicles in the Netherlands from 2020 to 2050, if no interventions are taken. The rest of the fleet remains driving on conventional fuels as stated in Fabius et al. (2020).

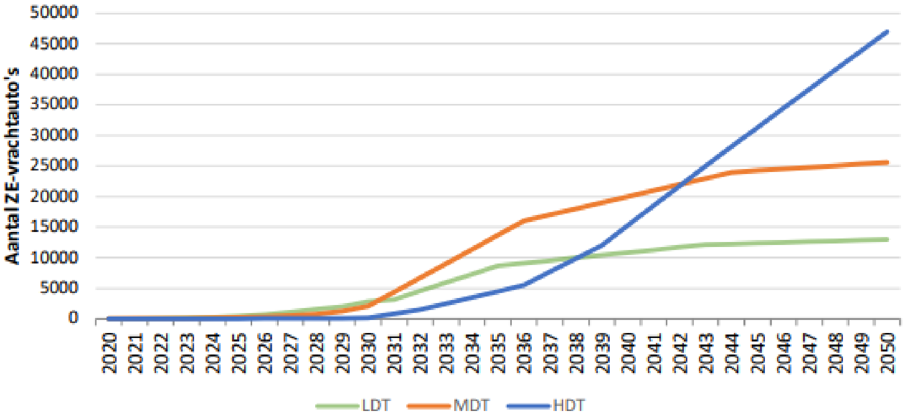


Figure 9. Uptake of battery electric and fuel cell electric vehicles

Note. Taken from “Transitiestudie verduurzaming wegtransport” by Fabius, B., van Sloten, R., & Aldenkamp, M. (2020)., p. 3, EVConsult. rijksoverheid.nl.

In the blue line no distinctions are made between the uptake of the BEVs and the FCEVs. However, in the text of Fabius et al. (2020) this distinction was made. In 2030, the expectations are that the share of zero-emission freight transport in the heavy-duty segment will be between 0-5% (out of a total of ~110,000 vehicles) of the total in the Netherlands. This share is expected to mainly consist of battery-electric trucks as they are economically more interesting than fuel cell electric trucks. The TCO of BEVs was thus lower than the TCO of FCEVs (Fabius et al., 2020). Currently, 0.16 % of the fleet in the Netherlands already consists of battery electric vehicles (BEVs) and 0.01 % of fuel cell electric vehicles (FCEVs) (Netherlands Enterprise Agency, 2022). The demand of BEVs is small, mainly due to the limiting factor of a short range. However, various manufacturers, including Nikola-IVECO, Tesla and Volvo, are already producing prototypes with a larger range in this segment. Manufacturers intend to produce more battery-electric heavy-duty trucks in the coming years, but only small series are expected around 2024/2025 (Fabius et al., 2020). The current production of FCEVs is even smaller compared to BEVs. Hyundai is one of the few manufactures that produces hydrogen trucks currently, some other manufactures are in the testing phase. There are also parties like Emoss that convert conventional vehicles into hydrogen vehicles. These manufacturers also partly determine which direction regarding energy carriers is taken in order to achieve the climate targets. The climate targets are set by governments on global, European or national level according to Fabius et al., (2020).

From 2030 and onwards the TCO of battery electric vehicles for heavy-duty transportation is predicted to be the most attractive, even more attractive than the TCO of diesel. Consequently, an uptake of BEVs is expected as shown in an increase in the blue line in figure 9. Regarding the fuel cell electric trucks the TCO improves over time, but remains smaller than the TCO of BEVs (Tol et al., 2023). Therefore, a smaller uptake of FCEVs compared to BEVs is assumed. After 2040 the TCO of BEVs is also forecasted to be most attractive, followed by diesel, after FCEVs and least attractive e-diesel.

Based on the given data of Fabius et al. (2020) and the Netherlands Enterprise Agency (2022), the forecasts on the uptake of zero-emissions are made and can be found in appendix D.

For the use of conventional diesel, biodiesel and e-diesel, the manufacturers of heavy-duty vehicles do not have to alter their current strategy, since the existing vehicles can be used to a large extent according to Cunanan et al. (2021) and Tol et al. (2023). The existing infrastructure can also be used to a large extent. However, it is important to remark that the e-diesel fuel is commercially available only after 2040 (Tol et al., 2023). Green hydrogen is predicted to be available in 2030 (Tol et al., 2023).

Currently, the infrastructure for BEVs which would be recharging stations and for FCEVs the hydrogen refueling stations remain limited (Tol et al., 2023). The European Union proposed a regulation named the Alternative Fuel Infrastructure Regulation (AFIR), in which recharging stations are made available by 2025 and hydrogen stations are available by 2030 (Tol et al., 2022).

The technique of the catenary electric road system is already available, but a construction period depending on the length of the corridor is required to build the system (Bateman et al., 2018).

3.3 Definition of the zero-alternative and strategies

In this paragraph 3.3 an answer is provided for sub question III. The strategies are aligned with the most promising energy carriers which are selected based on the literature review. The promising energy carriers identified by the literature review are battery electric, hydrogen (green, gaseous) and e-diesel. The promising energy carriers are either stimulated by subsidy or the usage is made obligatory in the strategies. The catenary electric road system was also found to be promising and is therefore also included in a sub strategy I.B. The zero-alternative comprises mainly the continuation of diesel by the heavy-duty fleet.

Relevant factors like the availability of the energy carrier, the availability of the corresponding infrastructure and the total cost of ownership (TCO) predictions, which are found in the literature review are acknowledged in the strategies. For example, e-diesel is made obligated in strategy III after 2040, because before 2040 e-diesel is not commercially available yet. The relevant factors and the climate targets are mentioned in the timeline. This is shown in figure 10. In line with these considered factors and climate targets throughout time, the zero alternative and the strategies are made. To make the strategies as realistic as possible, proposed and current legislation and (tax) policies are also considered. In the strategies the policy instruments of either stimulation by subsidy or obligation are used. The strategies could be implemented by the Dutch government and the Port Authority. The zero-alternative and the strategies are shown in figure 11.

The zero-alternative and the strategies are further outlined in more detail in terms of possible adaptation to the environment and amount subsidy provided in the parts zero-alternative and strategy I – III. The decisions that are made in the three strategies are explained and supported by the literature review.

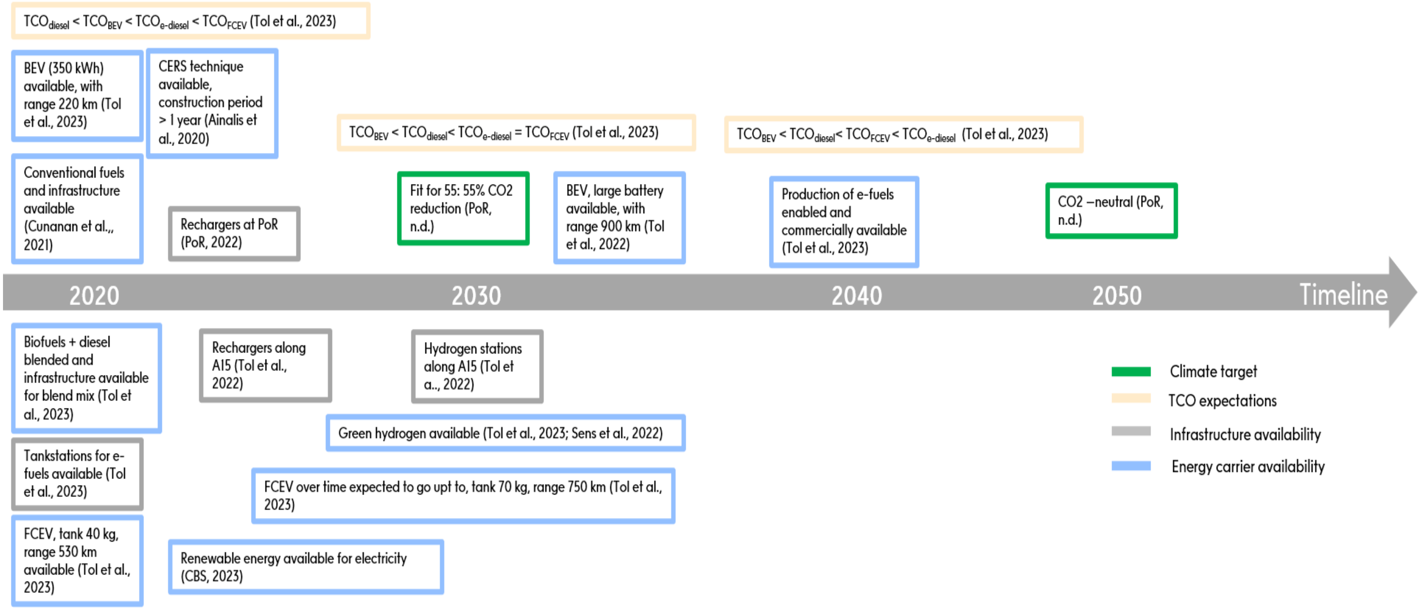


Figure 10. Timeline of important remarks for considered energy carriers

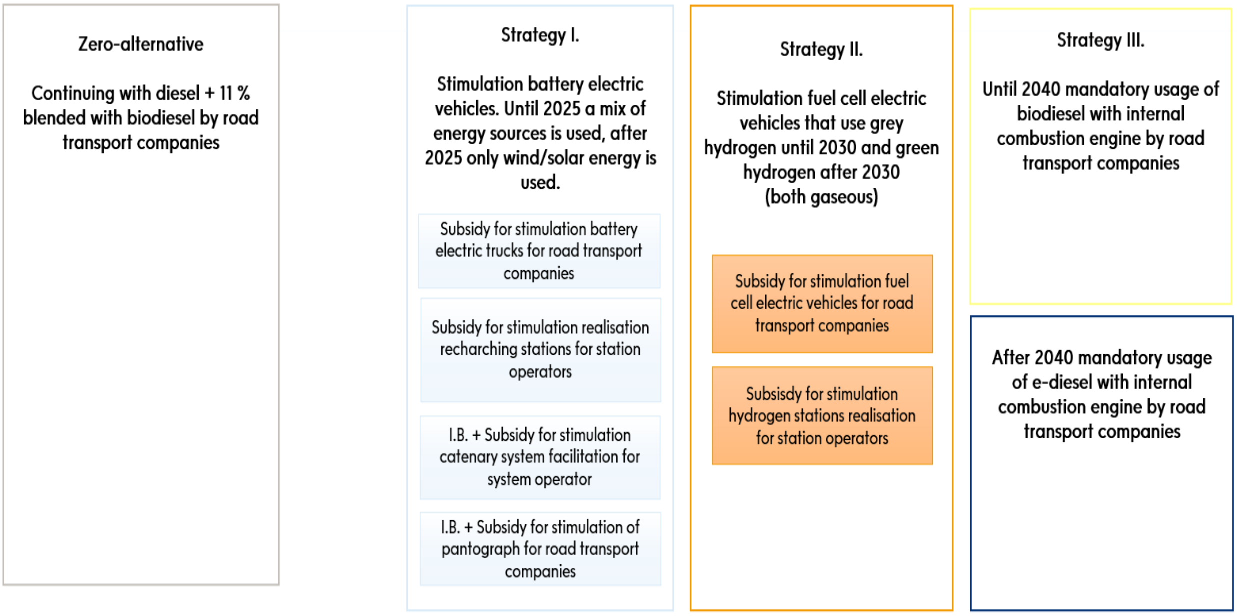


Figure 11. The strategies aligned with the literature review

Note: diesel serves as a reference point in the zero-alternative and biodiesel serves as an intermediate option for the third strategy. Both are included, but are not part of the most promising decarbonization energy carriers based on the literature review.

Zero-alternative: Continuing with a blended mix of diesel + 11 % biodiesel heavy-duty trucks with internal combustion engine

The zero-alternative is the business-as-usual scenario, which is the most likely development in case no policy interventions take place to alter the current situation (Renes & Romijn, 2013). In the zero-alternative, most road transport companies will drive in a conventional heavy-duty vehicle with an internal combustion engine based on the Cunanan et al. (2021). No subsidy will be provided for the purchase of diesel vehicles in the zero-alternative. In addition, no adaptations will be made to the refueling infrastructure, since according to Cunanan et al. (2021) the existing infrastructure can be used.

According to the Ministry of Economic Affairs and Climate (2019), the European Union agreed that in 2020 at least 10% of the fuel in transport should consist of alternative fuels, such as biofuels. Furthermore, if the minimum quantity for biodiesel per diesel = 109 L / 1000 is exceeded, a refund can be received on the excise duty (Belastingdienst, 2023b). In this study it is assumed that the transport road transport companies are aware of this tax advantage and will therefore use a blended mix of at least this minimum quantity of 11 % in order to receive the refund. Thus, for the zero-alternative it is assumed that at least 11 % of the blended diesel + biodiesel mix consists of biodiesel.

It is important to remark that during the continuation of the zero-alternative, 0.16 % of the fleet already consists of battery electric vehicles and 0.01 % of fuel cell electric vehicles (Netherlands Enterprise Agency, 2022). There is a further uptake expected of these zero-emission vehicles in the zero-alternative without strategic interventions. There is an uptake forecasted of 38.5% of battery electric vehicles and 2.5% of fuel cell electric vehicles. This is based on the forecasts by Fabius et al. (2020). Furthermore, no restrictions will be set on zero-emission transport. It could be that road transport companies are already intrinsically motivated to purchase zero-emission vehicles. Moreover, the infrastructure suitable for the zero-emission vehicles that already is facilitated will also be considered in the zero-alternative. In the zero-alternative it is assumed that no vehicles will drive on e-diesel. This is based on the forecast of Tol et al. (2023) that e-diesel is only available after 2040.

The zero-alternative disregards the current strategic intervention of the European Union, the Dutch government and the Port Authority of Rotterdam. These strategic interventions were mentioned in the introduction. The European Union proposed a regulation that makes it mandatory for member states to build recharging and hydrogen stations (Tol et al., 2022). The Dutch government provides a subsidy to entrepreneurs from 9 May 2022 when purchasing a truck that drives cleanly; electric or hydrogen as stated by the as stated by the Ministry of Infrastructure and Water Management (2022b). In addition, an extra subsidy of 22 million is allocated for hydrogen stations with associated trucks as stated by the Ministry of Infrastructure and Water Management (2022a). The Port Authority proposed a subsidy for recharging facilities (Voskamp et al., 2022). In this research the difference between strategies that stimulate different energy carriers is investigated. By disregarding the current (proposed) strategic interventions the difference between different energy carriers can be investigated. Therefore, the current (proposed) strategic interventions are left out of scope.

Strategy I. A: Subsidy for battery electric heavy-duty trucks and provisioning of recharging facilities

In this strategy I.A, the battery electric heavy-duty truck and recharging stations are promoted through a subsidy. Since this energy carrier was perceived as promising in the literature review. The subsidy will be provided by the Dutch government and partly by the Port Authority.

In this strategy I.A, a subsidy is provided for the purchase of battery electric trucks for a period of 5 years. This period will be from 2025 until 2030. This time horizon is chosen because of the $TCO_{BEV} > TCO_{diesel}$ until 2030 and after $TCO_{BEV} < TCO_{diesel}$ (Tol et al., 2023). Considering the TCO, after 2030 it will thus be more attractive to buy a BEV also without subsidy. The level of subsidy is the difference between the projected purchase price of battery electric vehicles (400 kWh, since 750 kWh is only available after 2030) and the purchase price of conventional diesel trucks, multiplied by the amount of vehicles that make use of the subsidy. It is assumed that the purchase price of the battery electric vehicle reduces through scale effects over time. The reduced purchase price is calculated based on the forecasted price reductions towards 2040 stated in Tol et al. (2023). The subsidy is spread over 5 years and in total it comprises around 415 million to stimulate the BEV purchase. The subsidy is available for road transport companies in order to support making their fleet zero-emission. The subsidy could offer an additional 15 % of the BEV-fleet support for battery electric vehicles in 2025 compared to the reference-strategy. The already projected uptake of battery electric vehicles stated in Fabius et al. (2020) could also make use of the subsidy. The percentage of the fleet that could make use of the subsidy to purchase BEVs could be increased each year with 5 % until 2029, thus 20 % in 2026 and 25% in 2027. In 2029 the subsidy will not take effect anymore and the money that was available in this strategy also reached its limit.

In line with the proposed Alternative Fuel Infrastructure Regulation (AFIR) stated in Tol et al (2022), every 60 km the building of a recharging station along the highway will be stimulated by the Dutch government in form of a subsidy before 2025. The building of a station in the port area of Rotterdam and in Duisburg will also be stimulated by subsidy. Currently, at the existing recharging places along the highway, which are mainly owned by company FastNed, the heavy-duty vehicles above 7.5 tons are not welcome. Vehicles heavier than 7.5 tons are not welcome at the stations mentioned by FastNed in the mail contact. Mainly due to safety reasons related to passenger vehicles. Furthermore, at the older (arch) stations it is not possible to get to the station with a high vehicle (max. 2.75 m). At the moment FastNed is investigating which locations might already be suitable or which actions need to be taken to make them suitable (Blauuw, personal communication, 2023). However, in this strategy due to the urgency for the compliance with the AFIR by 2025, it is assumed that new stations are built. The new stations will partly be subsidized for 50 % of the building costs of the recharging station. The total subsidy for recharging stations in this strategy comprises an amount of 4 million euros and takes effect for 2 years from 2023 to 2024. The building costs are not fully covered, since the demand of recharging already increases indirectly through the stimulation of battery electric vehicles. The percentage of 50% is similar to the proposed strategy by the Port Authority for the subsidy for the provisioning of recharging stations. The subsidy that covers a part of the building costs will be available for the station operator.

Considering the production process for the electricity, ‘an average mix’ as stated in Klein et al. (2020) of resources is assumed until 2025. This average mix implies a mix of energy resources. After 2025, it is assumed that wind or solar energy will be available. Since CBS (2023) stated that in 2022, 40 percent of total electricity production will come from renewable sources, which was an increase by 20 percent compared to a year earlier. This increase is assumed to be continued. Therefore, after 2025 renewable energy would be available for driving with battery electric vehicles.

Strategy I.B: Subsidy for battery electric heavy-duty trucks with a pantograph and the provisioning of recharging facilities and a Catenary Electric Road System

The catenary electric road system (CERS) was also found to be promising in the literature review, therefore this strategy I.B is made which stimulates the usage of this system. Strategy I.B is a sub strategy of strategy I and quite similar to strategy I.A. The difference is that in this strategy the building of the CERS and purchase of the pantograph system for trucks is also stimulated.

The level of subsidy provided in this strategy I.B is the difference between the projected purchase price of battery electric vehicles including the costs for the pantograph system and the purchase price of conventional diesel trucks, multiplied by the amount of vehicles that make use of the subsidy. It is assumed that the purchase price of the battery electric vehicle including the pantograph system reduces through scale effects over time. The reduced purchase price is calculated based on the forecasted price reductions towards 2040 stated in Tol et al. (2023) and Ainalis et al. (2020). The subsidy comprises an amount of 460 million euro spread over a period of 5 years to stimulate the purchase of battery electric trucks with a pantograph system. The pantograph system is compatible with the CERS. The subsidy is available for road transport companies in order to support making their fleet zero-emission from 2025 until 2030. The subsidy could offer an additional 15 % of the BEV-fleet support for battery electric vehicles and a pantograph system in 2025 compared to the zero-alternative. The already projected uptake of battery electric vehicles stated in Fabius et al. (2020) could also make use of the subsidy. The percentage of the fleet that could make use of the subsidy for BEVs + pantograph system could be increased each year by 5 % until 2029. Thus, 20 % in 2026 and 25% in 2027. In 2029 the subsidy will not takes effect anymore and the money that was available for the subsidy also reached its limit.

In line with the proposed Alternative Fuel Infrastructure Regulation stated in Tol et al (2022), every 60 km along the highway the building of a recharging station will partly be subsidized by the Dutch government. The building of one recharging station in the port area of Rotterdam and one recharging station in Duisburg will also be stimulated by subsidy. The new stations will partly be subsidized for 50 % of the building costs of the recharging station. The percentage of 50 % is similar to the current strategy by the Port Authority on the provisioning of infrastructure for zero-emission heavy-duty transport. The subsidy comprises an amount of 4 million and is two years available from 2023 to 2024. The building costs are not fully covered, since the demand of recharging already increases indirectly through the stimulation of battery electric vehicles. The subsidy for a part of the building costs will be available for the station operator.

In addition, the Catenary Electric Road System will be partly subsidized by the government for 50 % of the building costs. The full costs are not covered, since the subsidy of the pantograph system also increases the demand for the usage of the CERS. The subsidy for the CERS comprises 540 million and takes effect in 2023 for only 1 year. This period of 1 year comprises the construction period for CERS as stated in Ainalis et al (2020). According to Rijkswaterstaat

(2021), it is obligated that there is an obstacle free zone of 13 meters from the highway lanes. Otherwise, a barrier must be placed in between. However, it is assumed that either the barrier is already there, which would mainly be in the Randstad area, or that there is sufficient space without obstacles.

Strategy II: Subsidy for fuel cell electric hydrogen heavy-duty trucks and provisioning of hydrogen stations

Gaseous hydrogen used in a fuel cell electric heavy-duty vehicle was found to be promising in the literature review. Therefore, in this strategy II the usage of gaseous hydrogen in a fuel cell electric heavy-duty vehicle (FCEV) is stimulated. Preferably the usage of green hydrogen is promoted considering the environmental benefits of green hydrogen.

The usage will be stimulated through subsidies for the purchase of fuel cell electric hydrogen trucks. The subsidy is available for road transport companies in order to support making their fleet zero-emission. The subsidy should increase the demand for fuel cell electric vehicles. It should make the purchase price decline, since more FCEVs are bought. Thus through scale advantages the purchase price is lowered. The reduced purchase price is based on the purchase price reductions of the fuel cell electric vehicles stated in Tol et al. (2023). The amount of subsidy is the difference between the projected purchase price of fuel cell electric hydrogen vehicles and the purchase price of conventional diesel trucks, multiplied by the amount of heavy-duty vehicles that make use of the subsidies. The subsidy comprises an amount of 670 million and will be provided for during a period of 5 years, from 2025 until 2030. The subsidy offers support for an additional 15 % of the FCEVs-fleet to purchase the fuel cell electric vehicles in 2025 compared to the zero-alternative. The purchasers that were already intended to purchase a FCEV based on the forecasted uptake of Fabius et al. (2020) could also make use of the subsidy. The subsidy available could increase the percentage of the FCEVs-fleet purchasers each year by 5 % until 2029. Thus, 20 % in 2026 and 25% in 2027. In 2029 the subsidy will not takes effect anymore the money that was available also reached its limit.

In line with the proposed Alternative Fuel Infrastructure Regulation stated in Tol et al. (2022), every 150 km along the highway the building of the hydrogen refueling station will partly be subsidized. In addition, at the port of Rotterdam and in Duisburg a hydrogen station will partly be subsidized. The building of new stations will partly be subsidized and should cover 50 % of the building costs of the hydrogen stations. The subsidy comprises an amount of 15 million euros. The subsidy takes effect for a period of 2 years from 2023 to 2024. The building costs are not fully covered, since the demand of hydrogen already is increased indirectly through the stimulation of fuel cell electric vehicles. The percentage of 50 % is similar to the current strategy by the Port Authority on the provisioning of infrastructure for zero-emission heavy-duty transport. The subsidy to cover the building costs for the hydrogen refueling stations are available to the hydrogen station system operator.

Considering the production process of hydrogen, hydrogen can be used with renewable energy from 2030. Before 2030 other forms of production hydrogen are required which are less sustainable, this so-called grey hydrogen is therefore used until 2030. This is based on the assumptions of Tol et al. (2023) that green hydrogen scores positive on applicability and flexibility in 2030 onwards.

Strategy III: Mandatory use of biofuels until 2040 and e-diesel after 2040 for heavy-duty transportation

E-diesel was also found to be a promising energy carrier in the literature review. Therefore, in this strategy the usage of e-diesel will be mandatory after 2040. The year 2040 is based on the fact that after 2040 e-fuels will be commercially available according to Tol et al. (2023). Other forms of zero-emission heavy-duty transportation are also allowed in this strategy.

Before 2040, regulation will make it mandatory heavy-duty road transport to blend conventional fossil fuels with biofuels from 2025 until 2040. According to the Ministry of Economic Affairs and Climate (2019), the European Union already agreed that in 2020 at least 10% of the fuel in transport should consist of alternative fuels, such as biofuels. In this strategy similar policy is applied. An advantage of longer continuation usage of the blended mix of diesel + biodiesel is that the tax on fossil fuels can also be levied for a longer time. This results in a larger income for the Dutch government and thus a benefit for society.

Biofuels can thus serve as an intermediate fuel, this was also stated in Tol et al. (2023). As mentioned in the literature review biofuels are not part of the most promising energy carriers, since solely relying on biofuels will not be sufficient to reach the climate target. However, until 2040 it serves as an 'bridging' fuel in time until 2040, until e-diesel is available.

To a large extent biofuels and e-diesel can be used in the conventional vehicles with an internal combustion engine and both fuel can be used at the conventional refueling stations (Tol et al., 2023). Therefore, no further subsidies will be provided for either the purchase of vehicles or refueling stations. For the implementation of this strategy, only restrictions will be set to obligate the usage of the e-fuels or other forms of zero-emission transport.

For the implementation of this strategy, the European CO_2-legislation for heavy-duty vehicles that sets standards for the tailpipe emissions of HVDs over the years, also needs to be altered. The standards are currently tank-to-wheel based (Tol et al., 2023) and must be changed into legislation that regards the level of emissions from a well-to-wheel scope (Prussi et al., 2022). This implies that emissions from the refueling and usage process are currently only considered. While the emissions from the production process are disregarded in the regulation. For the implementation of this strategy the emissions from the production process should also be considered. This is based on the idea that e-diesel has the potential for zero-emission from a well-to-wheel scope, but not from a tank-to-wheel scope as mentioned in Prussi et al. (2022).

4. Conceptualization of effects

In this chapter the costs and benefits for the zero-alternative and proposed strategies that should be taken into account in the social-cost benefit analysis are conceptually defined based on the additional literature review and own analytical thinking. This is shown in figure 12 and this provides an answer to sub question four. An explanation on why the costs and benefits are included in the zero-alternative and the strategies is given in paragraph 4.1 – 4.3. Generally speaking, the costs and benefits are included if a difference with the zero-alternative is identified. For example, in the zero-alternative no subsidy is provided for zero-emission trucks, while in strategy I and II there is subsidy for stimulation of zero-emission vehicles. Therefore, for strategy I and II, the costs for the subsidy for the stimulation of zero-emission vehicles are included as effect. The corresponding formulas that are used in the model for all identified costs and benefits are also included in the paragraphs 4.1 – 4.3.

If the costs or the benefits take place in different years , the costs and benefits are multiplied by the discount rate of the corresponding year. The discount rate of 2.25 % is based on the guidelines of the Ministry of Finance (2020).

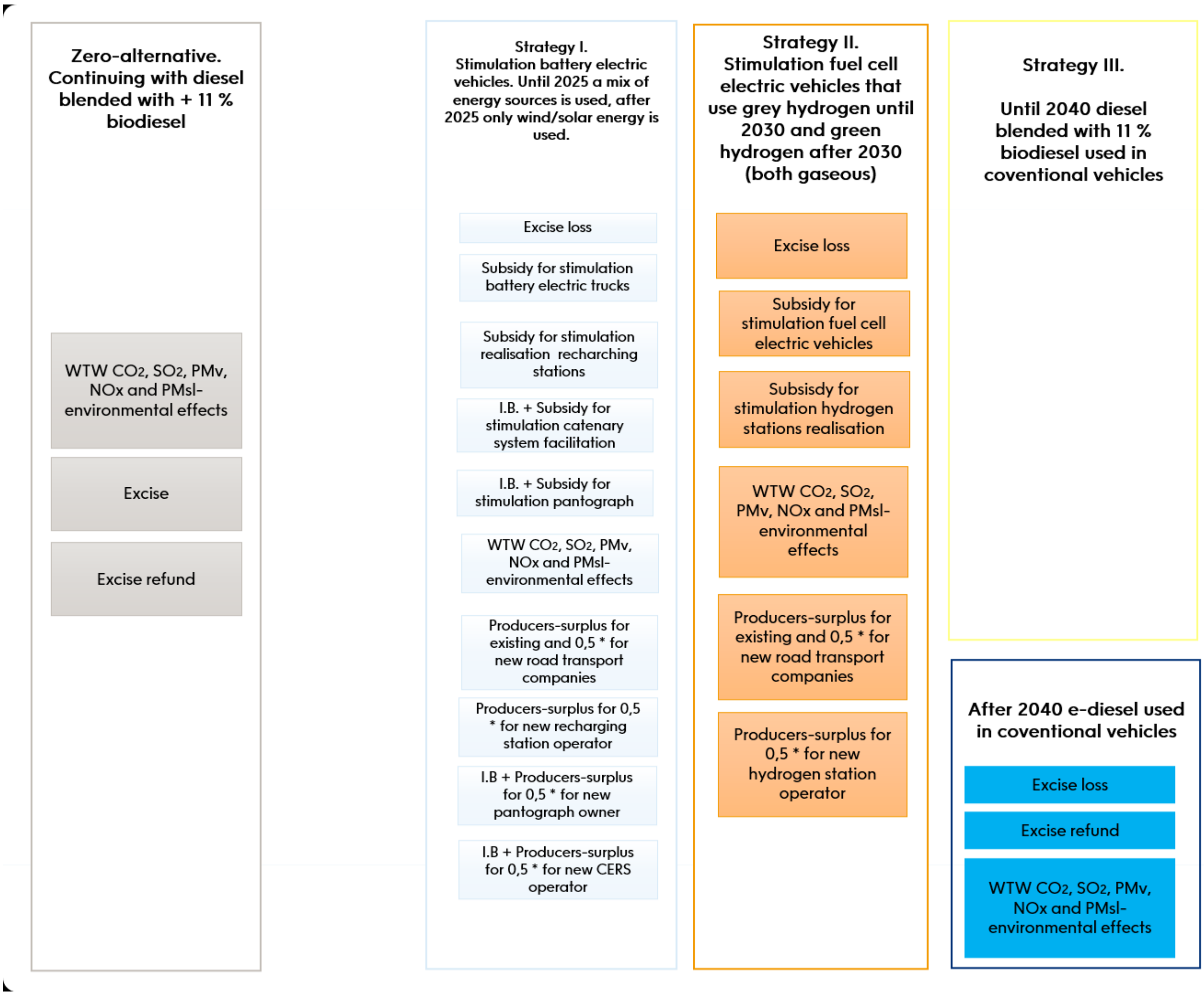


Figure 12. Costs and benefits considered per strategy

Conceptually speaking the identified costs and benefits can be categorized in four different sub groups, which are as follows;

1. The direct effects, consisting of benefits for the road transport companies and station operators that due to the subsidies can afford alternative technologies (in jargon: their producer-surplus increases);
2. The external effects (e.g. less CO_2 emissions);
3. The indirect effects, consisting of fuel tax losses;
4. The societal costs, consisting of the subsidy.

The identified effects will be discussed in this order. An explanation of why these effects are included is given based on the additional literature review and analytical thinking.

4.1 Direct effects (change in producer-surplus)

In this paragraph the direct effects are discussed. These consist of the Benefits for the road transport companies and station operators, in jargon named the change of producer-surplus. It is the utility that they receive from the subsidy.

The change in producer-surplus is the only direct effect identified. This effect is included for strategy I.A, I.B and II. Similar to the document of Annema et al. (2021), in which an example is given for a subsidy of zero-emission-techniques and the producer-surplus is included. The producer-surplus is similar to the consumer-surplus, but then for companies (Annema et al., 2021). In this case the road transport companies, the station operators and catenary electric road system owner. The companies receive more utility also known as change in producer-surplus, when they get the subsidy. Therefore, the producer-surplus is only included for strategy I.A, I.B and II. Since only in these strategies a subsidy is provided. The subsidies were not provided in the zero-alternative and therefore a delta is identified. For strategy III the subsidy is zero, the producer-surplus is thus also zero and the delta with the zero-alternative is thus also zero.

First, the producer-surplus as a result of the subsidy for the stimulation of zero-emission trucks (ze-trucks) is explained. This line of reasoning applies to both the stimulation of battery electric trucks in strategy I.A and I.B and the stimulation of fuel cell electric trucks in strategy II. The aim behind the provisioning of subsidies is that currently the demand and supply for zero-emission trucks is low, mainly due to the high purchase costs of the ze-trucks. By the use of a subsidy for ze-trucks, the purchase price will be more competitive with conventional trucks and thereby will be stimulated. Therefore, it is more likely that road transport companies will buy ze-trucks and that manufacturers will therefore offer more ze-trucks. The behavior of these parties will thus be influenced by the subsidy. Mainly the road transport truck companies will directly benefit from this subsidy. By the support of the subsidy more road transport companies are willing to buy for the zero-emission truck. The road transport companies who only purchase a ze-truck if a subsidy is provided are new buyers, also named new producers. However, there were also road transport companies who were already willing to buy the higher initial price and these road transport companies can also benefit from the subsidy. These road transport companies are defined as already existing producers. There are thus two types of ze-trucks purchasers, also known as producers, that can be distinguished:

a.) The existing producers (who were already willing to pay the initial price)
b.) The new producers (only buy a ze-truck through the support of the subsidy)

The road transport companies that make use of the subsidy, both existing and new producers, receive utility from the subsidy. This implies there is an increase in the producer-surplus, which is shown in figure 13. The increase of the producer-surplus is an increase on the social-welfare and must therefore be included in the social-cost benefit analysis.

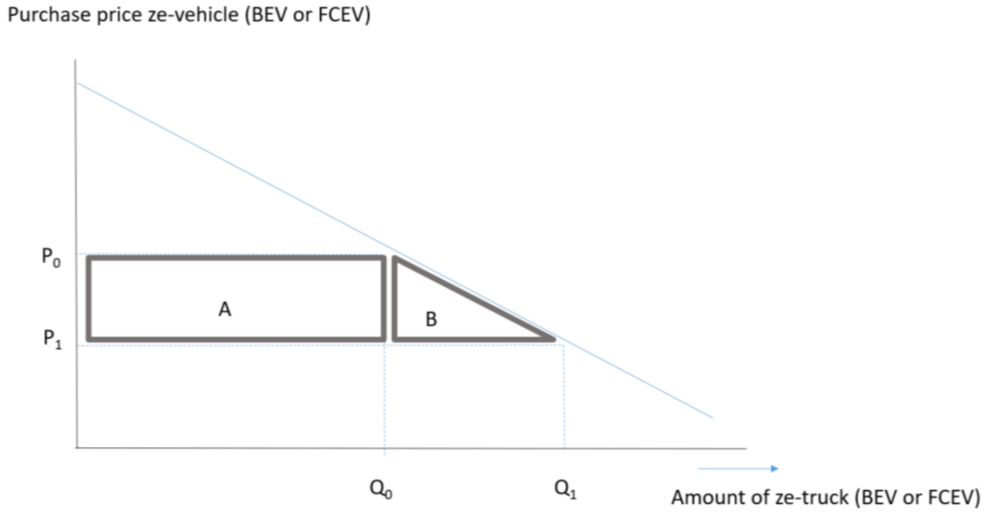


Figure 13. The increase in producer-surplus through subsidy based on Annema & van Wee (2021).

There are thus road transport companies who would already purchase the ze-vehicle even if no subsidy would be provided. This is shown in the zero-alternative. These road transport companies would already pay the initial P_o-price as can be seen in figure 13. Qo amount of ze-trucks would thus already be purchased as shown in figure 13. These road transport companies, the existing producers, can also make use of the subsidy and therefore they only have to pay P_1 in case of a subsidy. The existing producers receive all the utility from the subsidy and therefore a full producer-increase is identified. This is reflected in surface A in figure 13.

On the other hand, there are also road transport companies who make the decision to purchase the ze-vehicle through the subsidy. They would not purchase the ze-truck if no subsidy would be provided. This results in the fact that Q_1 ze-trucks will be purchased. There are thus 'new buyers' of the zero-emission trucks through stimulation of the subsidy, also named new producers as earlier mentioned. These road transport companies were not willing to pay the higher initial price P_o of the zero-emission truck , but are willing to pay the reduced purchase price P_1 for a ze-truck. These new producers form the surface B. Surface B is explained as follows: Suppose a subsidy of 1000 euros per ze-vehicle is provided. In the extreme, there is a new producer who was already prepared to purchase the ze-truck with a subsidy of only one euro. This new producer experiences an increase in the producer-surplus of approximately 1000 euros. Another extreme is a new producer who is only willing to purchase a ze-truck at a subsidy level of 999 euros. This new producer only experiences an increase in producer-surplus of 1 euro. An average of these new producers is 500 euros. Due to this reason, an average of the producer-surplus is taken for new producers and the so-called 'rule-of-half' is applied. This results in a half surface as shown in figure 13, surface B. Mind that the rule of half is thus only applied to the increase in producer-surplus of the new producers. All the old producers benefit fully from the subsidy and there is thus a full increase in producer-surplus. Therefore the rule-of-half does not take effect on them.

The producer-surplus only has effect in the years that the subsidy is present. If the subsidy does not have effect anymore, no utility can be derived anymore from the subsidy.

The total costs of ownership, which besides the purchase costs comprises the maintenance and logistic costs, are indirectly already included. Since it is assumed that individuals already take these factors into account while purchasing the vehicle. These factors are thus not included once more. There would be a double counting if these factors would be included once again according to Annema and van Wee (2021).

The producer-surplus increase as a result of the subsidy of recharging stations is included as effect for strategy I.A and I.B. The increase in producer-surplus as a result of the subsidy for hydrogen stations, is included as an effect for strategy II. For the subsidy for the realization of the recharging and hydrogen stations, after being referred to as zero-emission stations (ze-stations), the producer-surplus increases in a similar way as for the ze-trucks. The price of the ze-stations decreases from P_0 to P_1 and therefore Q_1 minus Q_0 new ze-stations are created. Since it is assumed that there were not already existing ze-stations, only new producers (new station operators) of the new ze-stations are supposed. This implies there could be two extremes of the turning point in purchasing the ze-stations through stimulation by subsidy. Therefore, the rule-of-half needs to be applied to the producer-surplus increase for the new ze-stations. There is thus only a surface B for the increased producer-surplus of the ze-stations. There is no surface A, since there are not already existing zero-emission station operators. As shown in the formula shown in figure 15, the rule-of-half is thus for all cases of increase in producer-surplus for ze-stations applied. The producer-surplus for the ze-stations only has effect in the years that the subsidy is present.

For strategy I.B, the producer-surplus as a result of the subsidy of the pantograph-system and the subsidy for the catenary electric road system is included as effect. A similar line of reasoning is applied as for the ze-stations. There are only new producers for the pantograph-system and for the catenary electric road system. There is thus no surface A conceptually speaking, but only a surface B.

The calculations for the increase in producer-surplus are stated in figure 14,15 and 16. The data that is used in the formula can be found in the appendix D.

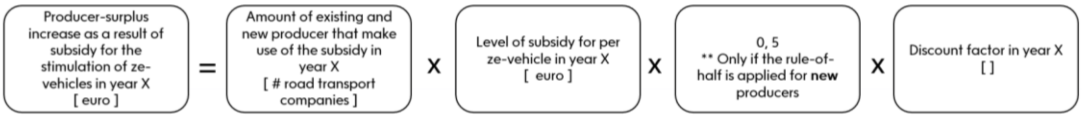


Figure 14. The producer-surplus as a result of subsidy for ze-trucks

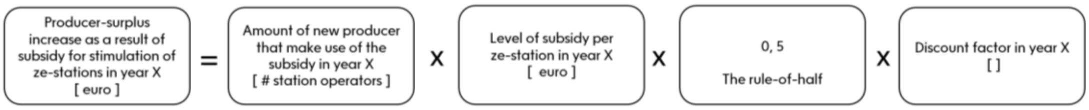


Figure 15. The producer-surplus as a result of subsidy for ze-stations

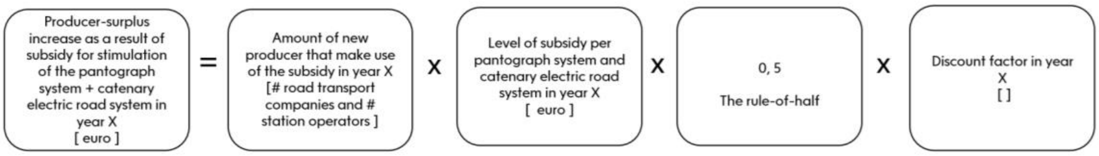


Figure 16. The producer-surplus as a result of subsidy for the pantograph system + CERS

4.2 External effects

In this paragraph the externalities are discussed. The externalities discussed are the environmental effects, noise pollution, congestion and the employment opportunities. It is also argued why some of these effects are left out of scope.

4.2.1 Environmental effects

In the case study, the environmental effects that heavy-duty transport causes, which are categorized as externalities are included in the social cost-benefit analysis (SCBA) for all strategies. For all strategies a delta caused by the environmental effects is identified compared to the zero-alternative. The environmental effects are the emissions caused through the usage of the energy carriers by the trucks. In case of the usage of more sustainable energy carriers as proposed in the strategies, there are less emissions compared to the usage of conventional fuels as in the zero-alternative. There are thus avoided emissions in the strategies compared to the zero-alternative. These avoided emissions are a benefit in the SCBA. For strategy III, until 2040 there is no difference with the zero-alternative, considering environmental benefits. Since a similar policy in strategy III is applied as in the zero-alternative until 2040 resulting in the same environmental consequences.

The environmental effects are included based on the additional literature review. Environmental effects can be included in the SCBA for transport- and infrastructure-projects according to Renes and Romijn (2013). It is also in line with the statement in Mouter et al. (2019) that individuals assign substantially more value to environmental impacts than in the more conventional cost-benefit analyses about transport projects. Therefore, in SCBA-case study environmental impact is included as an effect.

For the environmental effects in the case study, the whole chain from production until usage of the energy carrier will be regarded by taking the well-to-wheel (WTW)-scope for every strategy. This is based on the idea that the emissions are not shifted to another part of the chain. For example, the usage of the energy carrier by the truck could be very sustainable, while the production is very polluting. Therefore, the corresponding WTW-emission factors are taken into consideration. These WTW-emission factors include the emissions that are polluted in the entire chain. The WTW-scope is shown in figure 17 and comprises the production and conditioning at the source, the transportation and transformation at the source and near the market, the distribution and conditioning near the market and last also the refueling and the use phase as stated in Tol et al. (2023). The steps before the production at the resource are left out of scope. For all other included effects the scope of tank-to-wheel (TTW) is taken. The TTW-scope solely comprises the refueling and usage. Both scopes are shown in figure 17 from Tol et al. (2023).

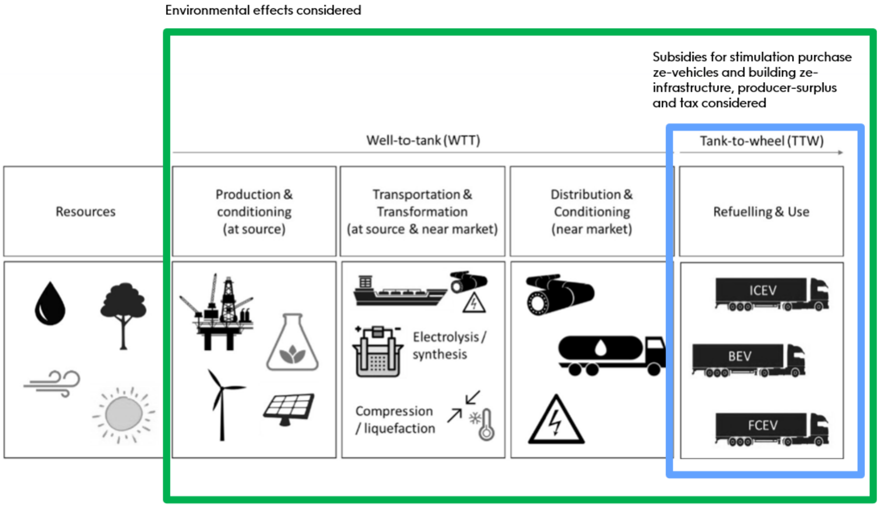


Figure 17. Well-to-wheel and tank-to-wheel scope

Note I. Taken from "The potential of e-fuels for heavy-duty road transport in the Netherlands," by Tol, D., Verbeek, M.M.J.F., Gaggar, S., Hulsbosch-Dam, C.E.C., Vredeveldt, A.W., van Zyl, P.S., van Ark E.J., Paschinger, P., Smokers, R.T.M. (2023). TNO, p.24, Available at Smartport.nl
Note II. The colored blocks are added to define the scope of the case study.

The environmental effects that are included are CO_2, SO_2, NO_x and PM-emissions. PM-emissions are both considered for emissions through combustion of PM_{10} and through wear of PM_{10}. PM_v is the abbreviation for PM_{10} by combustion and PM_{sl} is the abbreviation for PM_{10} due to wear (Klein et al., 2020). The emissions that the (conventional) heavy-duty trucks cause per km are retrieved from Klein et al. (2020).

The well-to-wheel greenhouse gas emissions of different energy carriers polluted by heavy-duty trucks are shown in figure 18. These WTW-emission factors are retrieved by Gustafsson, et al., (2021). These are thus the CO_2-emissions that are polluted from production until the usage by the heavy-duty vehicle.

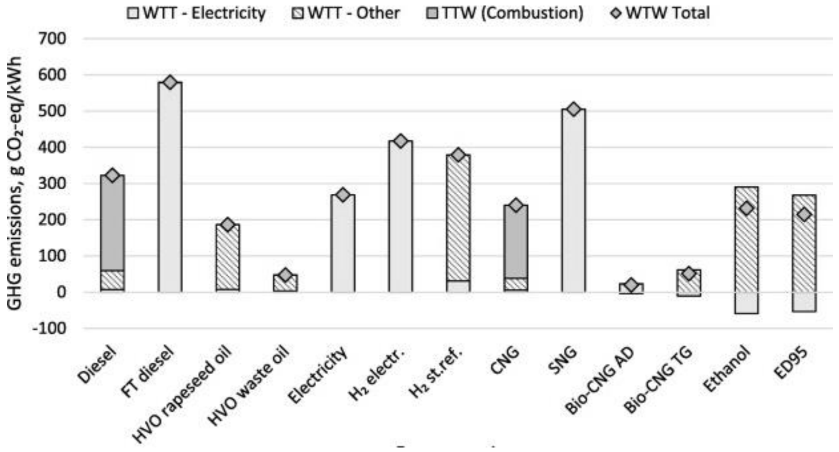


Figure 18. Well-to-Wheel emissions for heavy-duty transportation per energy carrier defined

Note I. Taken from "Well-to-wheel greenhouse gas emissions of heavy-duty transports: Influence of electricity carbon intensity." by Gustafsson, M., Svensson, N., Eklund, M., Öberg, J. D., & Vehabovic, A. (2021). Transportation Research Part D: Transport and Environment, 93, 102757.
Note II. For the WTW-emission factors in the Excel model the key figures of Klein et al. (2020) are used, since those were defined in a table for all types of energy carriers. These can be found in appendix E.

The polluted emissions are expressed per energy demand, in g/kWh as mentioned by Gustafsson or are expressed per distance driven in g/km as mentioned by Klein et al. (2020). For example, there is 1186 grams of CO_2 polluted per 1 km that is driven by a heavy-duty truck. In case of the usage of biodiesel only 16 % of these emissions are polluted. The total avoided emissions must be monetized before they can be included in the SCBA. The environmental prices of Bruyn et al. (2023) are used to value the avoided emissions. The valuations are shown in table 9. Some types of emissions are perceived as more harmful to the environment and are therefore valued more. There is thus a greater benefit received for society if these more harmful emissions are avoided.

Table 9. Environmental prices for emissions

	Scenario-Below [€ per kg]	Scenario-Central [€ per kg]	Scenario-Above [€ per kg]	Line of reasoning
CO_2	0.050	0.130	0.160	These are the environmental prices for air pollutant emissions in the Netherlands in 2021 stated in de Bruyn et al. (2023). They are expressed in in €/kg. There is a below-, central- and above variant for the prices. PM_v is the abbreviation for PM_{10} by combustion and PM_{sl} is the abbreviation for PM_{10} due to wear (Klein et al., 2020). Therefore, for both PM_v and PM_{sl}, the factors of PM_{10} are used, since another valuation of the PM-emissions remain unidentified.
SO_2	33.7	57.5	83.1	
PM_v (PM_{10} by combustion)	41.4	69.3	97.9	
NO_x	18.3	29.9	44.1	
PM_{sl} (PM_{10} due to wear)	41.4	69.3	97.9	

The formulas used for the environmental effects are shown in figure 19. The total emitted emissions are calculated based on the distance that is driven. After, it is calculated what the difference was in the proposed strategy with the zero-alternative. The costs for emitted emissions or benefits from avoided can be calculated by valuing the emissions. The valuation of the (avoided) emissions are calculated with the use of the environmental prices of de Bruyn et al., (2023), as earlier mentioned. The WTW emission factor Q, in the third formula, can also be expressed as a percentage relative to diesel. For example, biodiesel emits 16 % of the carbon emissions relative to diesel. The emission-factor of diesel [g/km] would then be taken and multiplied by 0,16.

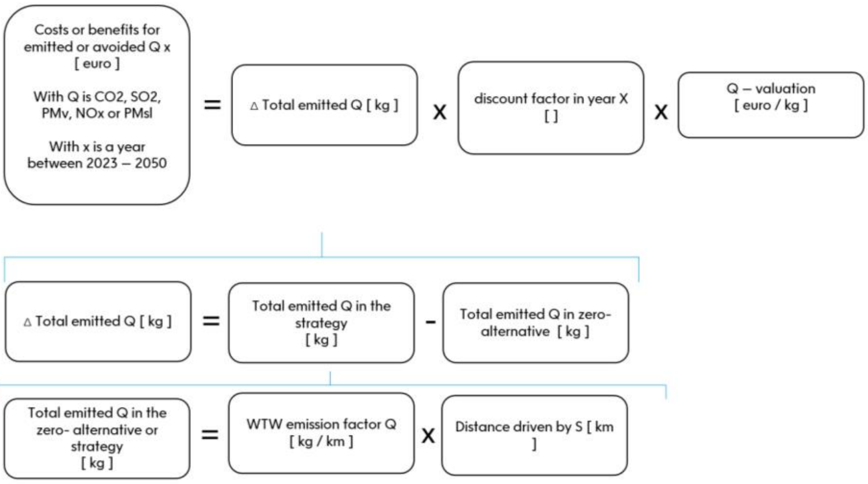


Figure 19. Externalities related formulas

4.2.2 Noise emissions, congestion and employment opportunities

According to Mouter et al. (2019) is noise pollution also an effect. However, in this study the noise emissions are left out of scope. Mainly because the level of noise remains approximately constant compared to the zero-alternative for all strategies. All types of energy carriers regarded in the case study including diesel, are in the same sound class of 80 + db(A) for the environmental prices stated by de Bruyn et al., (2023). There is thus no delta identified between the zero-alternative and the proposed strategies. Therefore, the noise pollution effect will not be included in the SCBA.

Congestion can also be seen as an environmental effect according to Wiegmans (2022) and safety can also be perceived as a factor individuals are willing to pay for according to Mouter (2019). However, in this study both factors are left out of scope in the SCBA, since it is assumed that for all types of energy carriers these factors for the heavy-duty truck remain the same.

The employment opportunities are also not included in the SCBA. Since it is assumed that the employees in the road freight transport sector make a shift to another sector, if the amount of employees in the road freight sector needs to be reduced. Therefore, the possible difference in employment opportunities in the road freight sector do not affect the level of welfare in society and the effect is not included in the SCBA case study. This assumption is similar to the assumption of Mouter et al. (2014), who states a redistribution of employment between regions and therefore no effects on the country.

4.3 Indirect effects

The indirect effects discussed are tax losses. There are all types of taxes levied that are relevant for the heavy-duty segment. In this paragraph, it is discussed if they should be taken into further consideration.

4.3.1 Fossil fuel tax losses and refund

Similar to the document of Annema et al. (2021) in which zero-emission techniques are stimulated by subsidy and the excise duty is included as a cost, in this study the losses of tax on fossil fuels are included in the SCBA-case study for all strategies I.A, I.B, II and III. The tax on fossil fuels is also known as excise. In case of the zero-alternative a high level of excise can be levied, but if the strategies are followed this levy is decreased. There would thus be a loss. This implies there is also a difference (a delta) between the zero-alternative and the strategies. Therefore, the excise duty is thus included in the SCBA. For strategy III, until 2040 there is no difference with the zero-alternative, considering levy of excise. Since a similar policy in strategy III is applied as in the zero-alternative until 2040 resulting in the same level of tax on fossil fuels. After 2040 there is a loss of excise in strategy III.

The excise duty is a form of tax levied for fuels, like petrol, diesel and LPG. If it is levied, it is perceived as a benefit for society. The excise duty on gas oil, also known as diesel, will be 516.25 euro per 1000 liters from the 1st of July 2023 (Ministerie van Algemene Zaken, 2022b). If the excise duty is not paid because a more sustainable energy carrier is used, it is a cost for society. A partial refund of the excise duty is also possible if the diesel is blended with biofuels for example. Refund is only received if the proportion of the bio-component exceeds a specified minimum quantity. The minimum quantity for biodiesel is 109 L / 1000 L (Belastingdienst, 2023b). In this study, it is assumed that the transport road transport companies are aware of tax advantage and will therefore use a blended mix of at least this minimum quantity in order to receive the refund. The refund of the excise duty is a cost for society. The formulas used for the excise duty are shown in figure 20 and the refund is shown in figure 21.Both are based on the Tax Authority (2023b). The data that is used in the formula can be found in appendix C, under the heading tax related data.

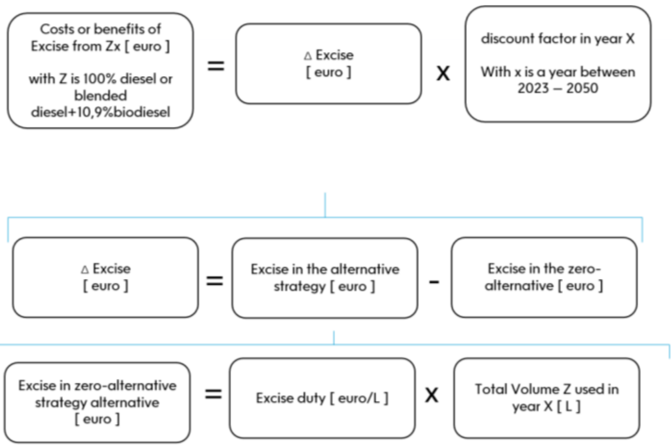


Figure 20. Excise duty formulas

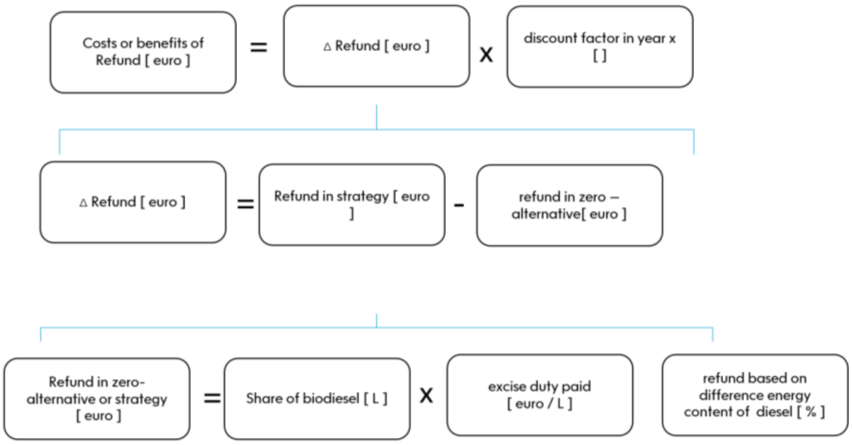


Figure 21. Excise refund formulas

4.3.2 Truck-tax per km, for heavy-motor vehicles and VAT

The truck-tax for domestic and foreign trucks which will be introduced in 2026 for the amount of kilometers driven on the Dutch roads is left out of scope, since the tariff remains the same for all distinguished strategies compared to the zero-alternative. The tariffs of the levy depend on environmental characteristics and the weight of a truck: the cleaner and lighter, the lower the levy (Ministerie van Algemene Zaken, 2022a; Overheid, n.d.). All types of heavy-duty vehicles regarded are classified in the same weight class above 3.500 kg, since this is the highest weight class it includes heavy-duty trucks. In addition, currently there is no separate class for zero-emission and low-emission transport, all fall under the same class of the EURO VI and cleaner - class (Ministerie van Infrastructuur en Waterstaat, 2020). In this study the most sustainable diesel trucks, the EURO VI, with the weight of more than 32.000 is assumed. Therefore, this diesel Euro VI trucks is also classified in the same tariff-class.

The heavy-motor vehicle-tax is left out of scope for similar reasons. If a truck makes use of the highway it must pay heavy-motor vehicle tax. The tariffs are decided based on the shafts of the vehicle, the time the trucks make use of the highway and the euro-emission class (Belastingdienst, 2023a), which remains constant in the proposed strategies compared to the zero-alternative.

The Value Added Tax is also left out of scope for the costs and benefits included. Since it is assumed the government wants to generate similar income for the energy carriers and would therefore adapt the VAT-percentage to generate the same benefit of the VAT.

4.4 Societal costs

The societal costs included in the SBCA are the subsidies given in strategies I.A, I.B and II. Subsidies are opportunity costs that can be spent otherwise (Annema et al., 2021). Therefore the costs that are made for the stimulation of the ze-emission heavy-duty vehicles, the ze-stations and the pantograph + catenary electric road system are included in the SCBA, since these cannot be spent otherwise by the government or the Port Authority. This is further explained in paragraph 4.3.1 – 4.3.3.

The provisioning of the subsidy is temporary. It will only be available for a few years. This is more plausible considering subsidies that are provided by the Dutch government are also only available for a few years. Furthermore, due to learning and scale effects the costs of the conventional trucks and the ze-trucks will eventually converge considering the changing total cost of ownership over time of ze-trucks. Road transport companies are therefore probably more willing to purchase the ze-truck from a certain point in time and station operators are also more willing to make the transition through an increased demand for the ze-energy carrier, the subsidy is therefore not necessary anymore in the long term. The pantograph system will be more attractive due to comfortable recharging and the catenary electric road system that is facilitated through the support of subsidy. This reasoning is based on Annema and van Wee (2021).

4.4.1 Subsidy for zero-emission trucks

The subsidy for ze-trucks is given in strategies I.A, I.B and II. The subsidy is for battery electric vehicles in strategy I.A and I.B and for fuel cell electric vehicles in strategy II. By the provisioning of subsidies the purchase of ze-trucks will thus become more competitive with conventional trucks and thereby will be stimulated. The provisioning of the subsidy-costs for the ze-vehicles are assessed by the difference of the ze-purchase price minus the purchase price of the conventional vehicles. This is based on the line of reasoning of Annema and van Wee (2021). The difference becomes smaller over time through the decrease in TCO of the battery electric vehicles and the decrease of the TCO of the fuel cell electric vehicles as mentioned by Tol et al. (2023). The difference between the costs for the purchase of the battery electric vehicles or the fuel cell electric vehicles and conventional trucks becomes thus smaller, this is also reflected in the subsidy. The formula used to calculate the costs for the subsidy for stimulation of the purchase of either the BEVs or FCEVs is stated in figure 22. The data used in this formula can be found in appendix D, under the heading vehicle related data.

$$\boxed{\begin{array}{c}\text{Costs for subsidy}\\ \text{for the purchase of}\\ \text{BEVs or FCEVs}\\ [\text{ euro / year }]\end{array}} = \boxed{\begin{array}{c}\text{Purchase costs of BEV (with a 400 kWh battery) OR FCEV}\\ [\text{ euro / vehicle }]\text{ - purchase costs of conventional truck}\\ [\text{ euro / vehicle }]\end{array}} \times \boxed{\begin{array}{c}\text{amount of BEVs or FCEVs in year x}\\ [\text{ vehicle }]\text{ - amount of BEVs in year x} - 1\ [\text{ vehicle}]\end{array}} \times \boxed{\begin{array}{c}\text{discount factor in}\\ \text{year x [ ]}\end{array}}$$

Figure 22. Subsidy for ze-vehicles formula

4.4.2 Subsidy for zero-emission stations

The subsidy for the stimulation of zero-emission stations is also given in strategy I.A., I.B and II. The new stations, either electric recharging or hydrogen stations, will be subsidized and should cover 50 % of the building costs. The building costs are not fully covered, since the demand of electricity or hydrogen already increases indirectly through the stimulation of battery electric vehicles or fuel cell electric vehicles. The subsidy for the recharging or the hydrogen stations should support the recharging or hydrogen station operator directly.

The maintenance costs are not further included since it is assumed that for the purchase of the stations this factor is already considered. Otherwise there would be a double counting. The tariffs for recharging, the hydrogen or e-diesel are not further included. It is assumed that the station operator already considers the tariffs prices before making the transition towards another energy carrier, in order to maintain a sound business.

The formulas used for the calculation of the costs for the subsidy of the stations are shown figure 23. The data used in this formula can be found in appendix D, under the heading station related data.

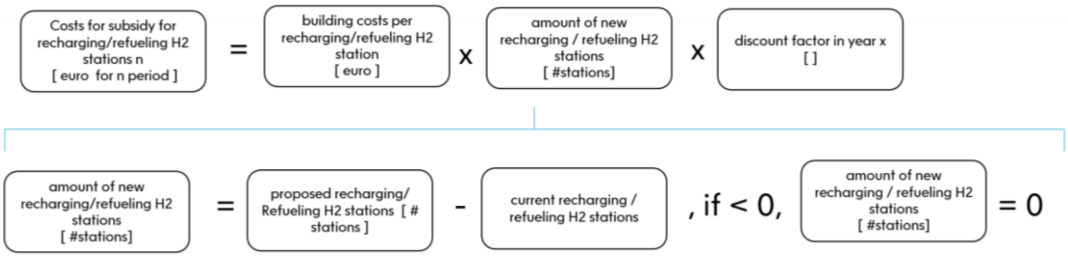


Figure 23. Subsidy for ze-stations formulas

4.4.3 Subsidy for the pantograph + catenary electric road system

For the strategy I.B., costs for the subsidy for the stimulation of the building costs of the catenary electric road system (CERS) are included. The subsidy for the stimulation of the pantograph-system f are also included as a cost in the SCBA. These formulas are shown in figures 24 and 25. Data used for in the formula can be found in appendix D, under the heading catenary electric road system related data.

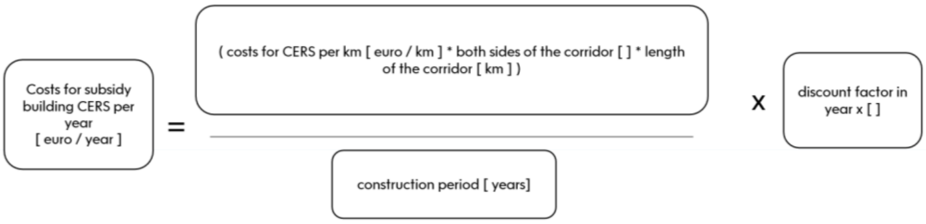


Figure 24. Subsidy for CERS formula

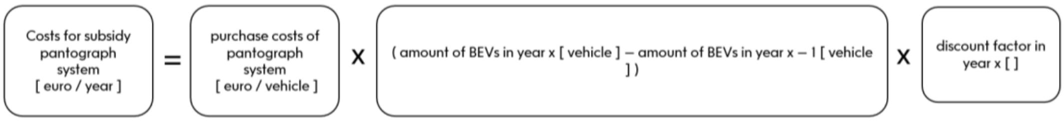


Figure 25. Subsidy for the pantograph system formula

5. Results development social-costs and benefits

In this chapter the results are given of the development of the social-costs and benefits if the decarbonization strategies for heavy-duty transport are followed. These results provide an answer to sub question five. In table 10 an overview is given of the final results to compare the socio-economic feasibility of the proposed strategies. It shows how much CO_2 -reduction is achieved in 2050 compared to the zero-alternative as a result of the strategy. The Net Present Value (NPV) and the benefit-costs ratio are also shown per strategy in table 10. These indicators serve as final measures through which the socio-economic feasibility of the strategies can be compared, a corresponding explanation is given later in this chapter. In table 10, the costs and the benefits are also presented per category (e.g. societal costs). All numbers are rounded.

In figure 26 the development of the CO_2-emissions from 2023 to 2050 per strategy is given. In figure 27 the costs and benefits are shown per category for each strategy in bar charts. The blue colors in the bar charts indicate the costs or benefits for the government and the Port Authority. The orange color in the bar charts indicate the costs or benefits for the private companies (the carriers and the station operators). As can be seen in the bar charts, all the costs are for the governmental parties and all the benefits are for the private parties if the strategies are followed. The environmental benefits in the bar chart of figure 27 are colored green, these are assumed to be for both public and private parties.

The graphs on the fleet development per strategy as a result of either a subsidy or making usage mandatory can be found in appendix G. The development of the SO_2, PM_v, NO_x and PM_{sl} -emissions are shown in the appendix H. Only a graph of CO_2-emissions are presented in this chapter, since the main focus in the study is decarbonization. Tables in which the costs and the benefits are provided per sub category (e.g. benefit for avoided NO_x) can be found in appendix I.

Table 10. Final results

Type of strategy → Overall insights ↓	**I.A. Stimulation battery electric vehicles**	**I. B. Stimulation battery electric vehicles + catenary electric road system**	**II. Stimulation fuel cell electric vehicles**	**III. Mandatory biofuels until 2040 and after e-diesel**
CO_2-reduction in 2050 compared to zero-alternative [%]	**- 50**	**- 50**	**- 30**	**- 35**
Net Present Value [euro]	**- 401,000,000**	**- 696,000,000**	**- 431,000,000**	**- 671,000,000**
Benefit-cost ratio [ ]	**0.8**	**0.7**	**0.8**	**0.4**
Direct effects [euro]	**629,000,000**	**923,000,000**	**1,073,000,000**	**0**
External effects [euro]	**724,000,000**	**724,000,000**	**505,000,000**	**400,000,000**
Indirect effects [euro]	**- 1,337,000,000**	**- 1,337,000,000**	**- 1,337,000,000**	**- 1,072,000,000**
Societal costs [euro]	**- 418,000,000**	**- 1,007,000,000**	**- 672,000,000**	**0**

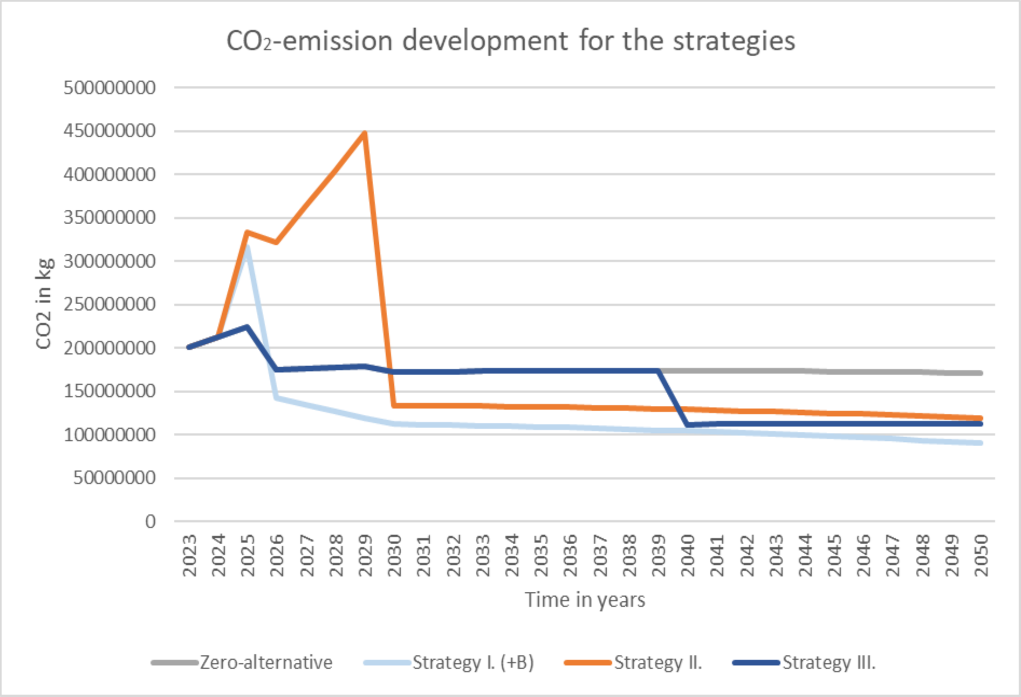


Figure 26. Development CO_2 emissions per strategy

As shown in table 10, all proposed strategies show negative NPVs compared to the most likely development if no strategic interventions take place and all benefit-costs ratios show a value below 1. This implies that the costs are higher than the benefits of the followed strategy compared to the zero-alternative. Considering the socio-economic feasibility, all the proposed strategies are not welfare enhancing. This means that the benefits do not outweigh the costs. Even with the environmental benefits included at the current environmental prices in the SCBA, the benefits do not outweigh the costs that are made to stimulate the usage of the zero-emission heavy-duty vehicles.

For all proposed strategies the climate targets are not achieved from a well-to-wheel perspective. As shown in table 10, reductions between the 30 – 50 % compared to the zero-alternative are reached in 2050 as a result of the strategies. However, the climate target of zero-emissions in 2050 is not achieved. Mainly because it is not made mandatory to drive with zero-emission vehicles. Therefore, in strategies I and II a percentage of the considered fleet remains driving on the blended mix of diesel + 11 % biodiesel. It could be that road transport companies and station operators were not incentivized sufficiently to purchase a zero-emission technology. For strategy III, the climate targets are also not achieved since the production process of e-diesel is not climate neutral yet by 2050.

For all strategies, there is a severe loss of tax on fossil fuels as shown in figure 27. The income of the government is reduced by this severe loss. This tax loss is a cost for society. The refund on the biodiesel is received by the road transport companies. The tax on fossil fuels can be levied less by the government due to the uptake of zero-emission vehicles. In the zero-alternative, the tax on fossil fuels can be maintained, because 60 % of the considered fleet remains driving on the blended mix of diesel + biodiesel until 2050. This percentage is based on the data of Fabius et al. (2020).

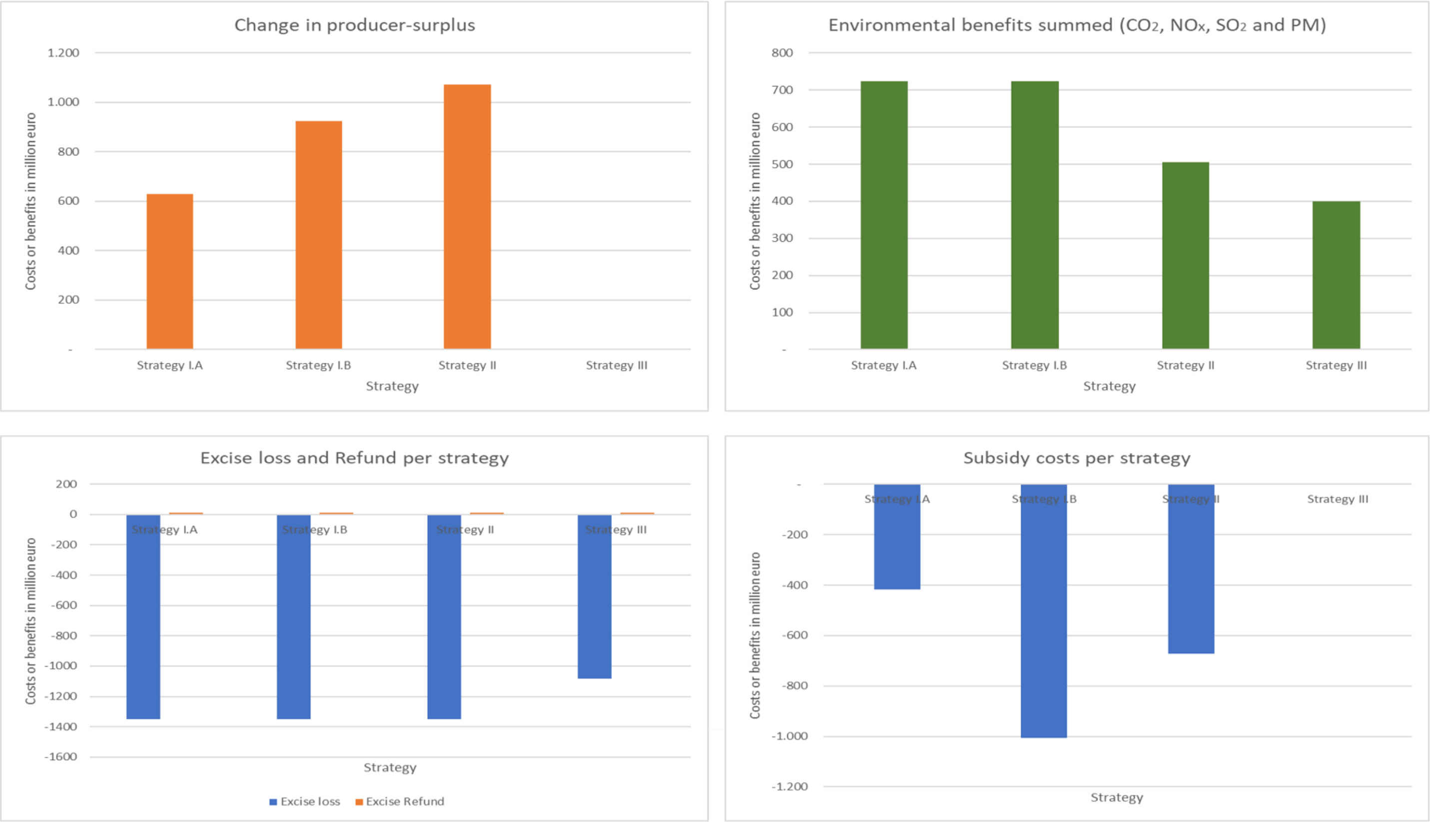


Figure 27. Costs and benefits per category

Strategy I.A is the most feasible strategy from a social-welfare perspective, considering the result of the Net Present Value in table 10. For the stimulation of battery electric vehicles of 400 kWh and the recharging stations along the highway of Rotterdam – Duisburg, a subsidy was provided around 420 million euros. Resulting in the effect that the climate targets towards 2050 are approached closer by 50 %, but are still not reached as shown in the graph of figure 26. This is caused by the 25 % of the considered fleet that still drives on a blended mix of diesel and biodiesel as shown in appendix G. Since in the strategy I.A zero-emission transport is not made mandatory. After 2025, there is a stronger decrease of carbon emissions seen in figure 26. This is mainly due to the stimulation of the battery electric vehicle by subsidy, which resulted in an extra amount of battery electric vehicles purchased of 15 % in 2025 and 5% cumulative increase until 2030. Furthermore, based on the data of CBS (2023) from 2025 it is assumed that only renewable energy from either solar, wind or biomass is used for production of electricity used in BEVs. Before 2025, there is a small increase in carbon emissions because the considered fleet grows given the growth factor of CBS (n.d.), the battery electric vehicles are not stimulated yet and last renewable energy is not yet available. Compared to strategy II, a lower subsidy needs to be provided for the same percentage of additional users of the subsidy for the zero-emission vehicles and recharging stations. Mainly due to the lower purchase costs of the battery electric vehicles than the fuel cell electric vehicles The costs for the stimulation of a recharging station are also lower than the costs for the stimulation of the hydrogen refueling station (Tol et al., 2023; Port of Rotterdam, 2022b).

In addition, strategy I has a higher level of total environmental benefits compared to strategy II, as shown figure 27. The main reason is that green hydrogen is only available after 2030 (Tol et al., 2023; Sens et al., 2022), while renewable energy for electricity is already available in 2025 (CBS, 2023). The earlier availability results in higher environmental benefits for strategy I. It can

be concluded that strategy I.A, is the most effective strategy considering the carbon emissions reductions with the least financial support by the government.
Strategy I.B results in a more negative Net Present Value compared to strategy I.A. This is mainly because the highest level of subsidy needs to be provided in order to stimulate the purchase of the pantograph system for road transport companies and to stimulate the building of the catenary electric road system for a system operator. As shown in figure 27, it can also be concluded that there are no additional environmental benefits from a well-to-wheel perspective compared to strategy I.A, because the same battery electric vehicles are used with the same characteristics as in strategy I.A. From a social-welfare perspective, it can be concluded that the stimulation of the catenary electric road system with the corresponding pantograph system is an undesirable strategic intervention.

For strategy II, there are less environmental benefits from a well-to-wheel perspective compared to strategy I.A. and I.B, as shown in figure 27. As shown in the graph of figure 26, there is a higher level of carbon emissions emitted compared to strategy I.A. and I.B in 2050. This is the case, because still 30 % of the considered fleet will drive on a blended mix of diesel + biodiesel as shown in appendix G, since zero-emission transport is not obligated. Furthermore, until 2030 there will even be a higher level of carbon emissions emitted in strategy II compared to the zero-alternative, because the purchase of fuel cell electric vehicles will already be stimulated by a subsidy, while the green hydrogen will not be available yet. The early implementation results in a high peak of CO_2-emissions as shown in figure 26. As shown in figure 26, after 2030 a decline is seen considering the carbon emissions of strategy II. The decline is the result of the availability of green hydrogen in 2030 (Tol et al., 2023; Sens et al., 2022). It can be concluded that strategy II is implemented too early. Considering the carbon emissions, it would be more desirable to stimulate fuel cell electric vehicles, thus indirectly the usage of hydrogen, later in time when green hydrogen is available.

The producer-surplus in strategy II as a result of the subsidy for fuel cell electric vehicles and hydrogen refueling stations are the highest, because the utility that the road transport companies and the station operators receive from the subsidy is high. Since there is already a percentage of 'existing producers' that receive the full utility. In strategy I.A and I.B the producer-surplus is smaller, because there are more 'new producers' that use the zero-emission technique. For these 'new producers' half of the utility is assigned. The producer-surplus for each strategy is shown in figure 27. The loss of excise duty in strategy II is smaller compared to strategy I, because there are more trucks that still drive on the blended diesel + biodiesel mix for which the excise can be levied.

For strategy III, no subsidy required for the fleet or the infrastructure since this the current fleet and infrastructure can be used. Therefore the shift towards e-diesel usage would be rather easy from a tank-to-wheel perspective (the refueling and usage part). Since no subsidy is provided, no utility is received from the subsidy. Therefore, the change in the producer-surplus is also zero. However, the environmental benefits in this strategy are the lowest compared to the other strategies. These low environmental benefits are a result of the production process of e-diesel that still has a high energy demand and emits carbon emissions. Furthermore, until 2040 95 % of the fleet remains driving on the blended mix of diesel and biodiesel. From a social-welfare perspective it can be concluded that given the current data, making e-diesel mandatory from 2040 until 2050 is an undesirable strategic intervention.

6. Results of uncertainty and sensitivity analysis

First, the factors that have a high level of uncertainty and a high level of influence are qualitatively discussed. Subsequently, the effects on the results of these uncertain factors with a high level of influence are quantitatively addressed. Last, the results of the sensitivity analysis are discussed.

6.1 Qualitative results of uncertainty analysis

Based on the findings of the literature review in chapter 3 and the results of chapter 5, the factors are identified and classified based on their level of uncertainty and influence on the results. All the identified factors are marked blue in figure 28.

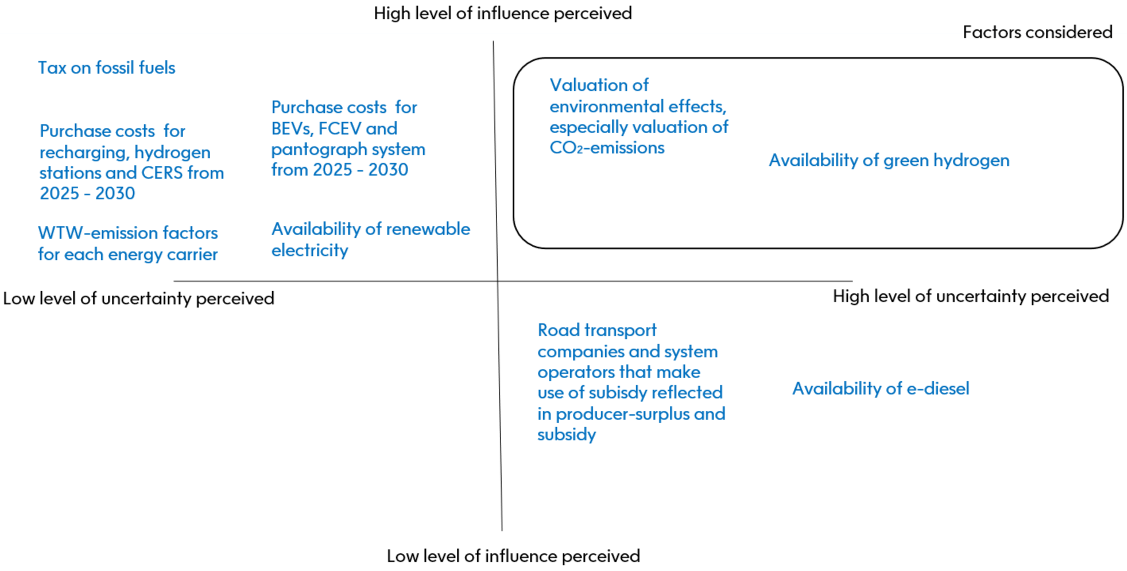


Figure 28. Observed factors of uncertainty and influence

The factors that are perceived as highly uncertain and have a high influence are the valuation of environmental effects, especially the valuation of carbon emissions and the availability of green hydrogen.

The valuation of CO_2-emissions is perceived as uncertain. If the climate crisis becomes more urgent it is plausible that the valuation for avoided CO_2-emissions rises. The valuation of the environmental effects have a high level of influence on the net present value as shown in chapter 5.

The availability of green hydrogen in 2030 is also perceived as uncertain. It is assumed that green hydrogen will be available in 2030 based on the data of Tol et al. (2023) and Sens et al. (2022). However, Plötz et al. (2022) perceives the availability in 2030 as uncertain. Since the results of strategy I (that stimulates renewable electricity) and strategy II (that stimulates green hydrogen) do not show a high difference, the assumption on green hydrogen might have a high level of influence on the results.

For the availability of e-diesel similar assumptions are made on the year of availability as the assumptions on green hydrogen. However, since the Net Present Value of strategy III, is not close to the Net Present Value of strategy I.A and II. a low level of influence on the results is perceived. The availability of renewable electricity has a lower level of uncertainty, since the availability is already forecasted in the near future, this makes influences over time less uncertain.

It would also be uncertain how many road transport companies and system operators make use of the subsidy. This is simply a reflection of economic behaviour, but it is also influenced by factors such as welfare prosperity. The amount of producers (users of the subsidy), is limited by the available budget of the subsidy, but within this limitation the difference of companies that can make use of the subsidy is large. It is questionable if the companies are sufficiently incentivized. However, for strategy I.A, I.B and II, it is assumed that the same level of additional road transport companies make use of the subsidy. Therefore, the level of influence is perceived as low.

The tax on fossil fuels has a low high level of influence since the results show extreme values compared to the other costs and benefits considered. However, the level of uncertainty is low since the tax on fossil fuels has already maintained a long time of conventional fuels. It is unlikely that the government would change the policy of tax on fossil fuels. The most imaginable scenario would be a stronger levy, in order to stimulate the switch from fossil fuels to more sustainable energy carriers.

It is likely that the purchase costs of zero-emission vehicles and infrastructure decline over time through technological developments and the advantages of economies of scale. This would mainly reflect in the producer-surplus and the level of subsidy for the stimulation of the purchase. However, a decline of the purchase costs already is assumed in the SCBA.

6.2 Quantitative results of uncertainty analysis

The uncertainty and level of influence of the valuation of CO_2-emissions of and the availability of green hydrogen in 2030 are also addressed quantitative.

The Net Present Values of the strategies are calculated for other CO_2-prices. The results are shown in figure 29. For the valuation of CO_2-emission higher prices are taken. Starting from the value of 130 euro per ton emitted CO_2, similar to the number of Klein et al. (2020), up to 800 euro per ton emitted CO_2.

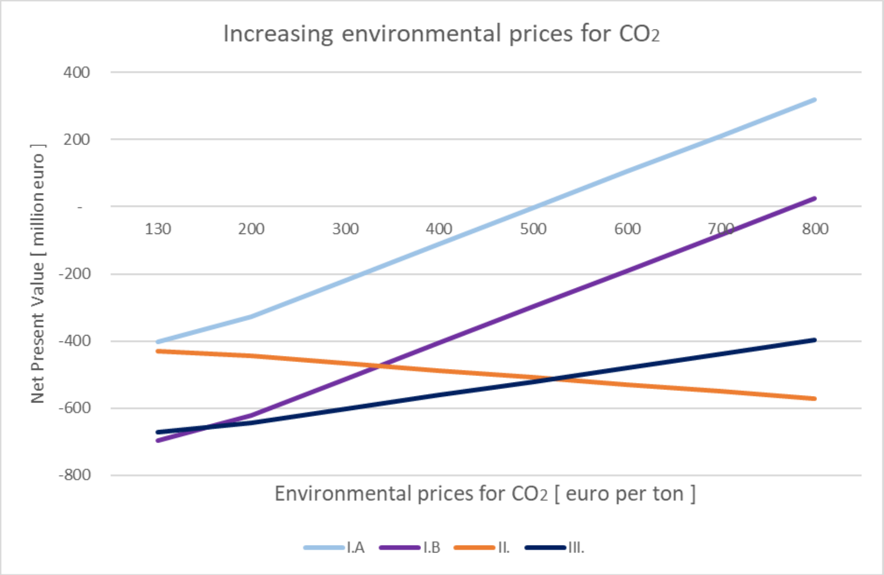


Figure 29. Change in NPV by increasing CO_2-prices

As shown in figure 29, all strategies become more welfare enhancing if the CO_2 prices rise except strategy II, which stimulates fuel cell electric vehicles. This is because in this strategy all the carbon emissions that are emitted from 2023 to 2050 are higher compared to the zero-alternative. The high peak of carbon emissions as earlier shown in figure 26 causes costs in strategy II. If the carbon-prices rises, the net present value becomes even more negative of strategy II. The Net Present Value of strategy I.A and I.B show the same changes in Net Present Value, since the same level of carbon-emissions are avoided. The Net Present Values become positive at a price of 500 euro per ton CO_2 for strategy I.A and around 800 euro per ton CO_2 for strategy I.B. This implies that the strategies become welfare enhancing at that level of CO_2-price. The Net Present Value of strategy III changes less, because the strategy avoids less CO_2-emissions from 2023 to 2050.

Second, the influence of the availability of green hydrogen is quantitatively addressed. The effect on the Net Present Value of strategies I and II are shown in figure 30. Only these two strategies are compared since the Net Present Values were both most promising and close to each other as shown in chapter 5. As shown in figure 30 the availability of green hydrogen does not affect strategy I, but does effect strategy II. This is plausible, since in strategy II the hydrogen is stimulated Thus, the results depend more on the availability of green hydrogen. If green hydrogen is only available after 2037, thus a delay of 7 years, the Net Present Value of strategy I would be twice the Net Present Value of strategy II. This implies strategy I is much more welfare enhancing than strategy II in case the green hydrogen is later available.

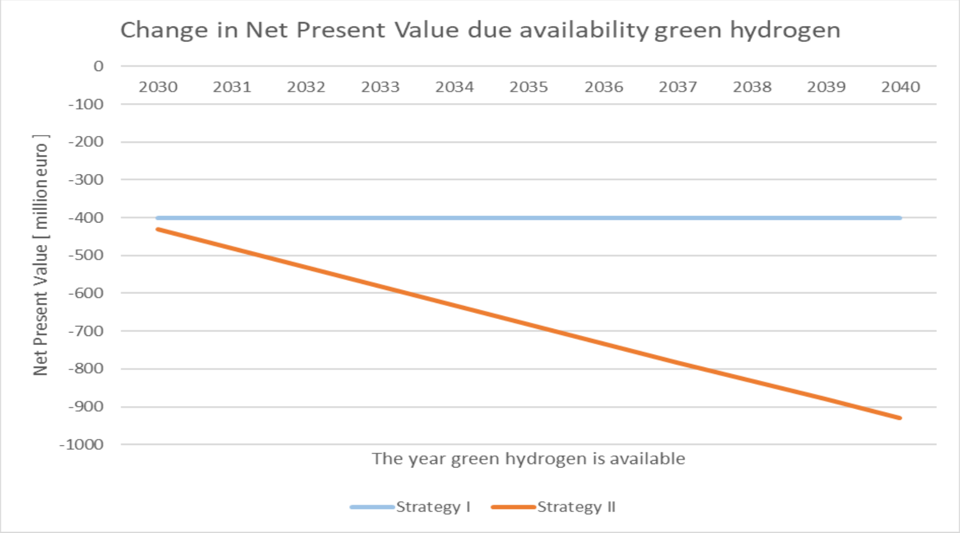


Figure 30. Change in NPV due to later availability green hydrogen

6.3 Results sensitivity analysis

The results of the sensitivity analysis that showed a change of more than 30 % in the Net Present Value of a strategy by increasing or decreasing an input variable by 10 % are shown in figure 31. The Net Present Values that changed less than 30 % by changing the input variable with 10 % are not shown in figure 31, but can be found in appendix J.

The results of the sensitivity analysis show that the Net Present Value of all strategies changes more than 30 % if the input variable of excise duty tariff is changed by - 10 % or + 10 %. This is intuitive, since the results in chapter 5 show that the strategies have severe impact on the excise levy. Therefore, it is plausible that a small change of 10 % in the excise duty has a big impact on the Net Present Value of all strategies. The other change of input variable by 10 % that showed an impact larger than 30 % o the Net Present Value, was the change of the purchase costs of the fuel cell electric vehicle in 2020. This is also intuitive, since this input variable effects the producer-surplus of strategy II and the level of subsidy.

Concluding, the model is sensitive to a change in the excise duty tariff and the purchase costs of fuel cell electric vehicles.

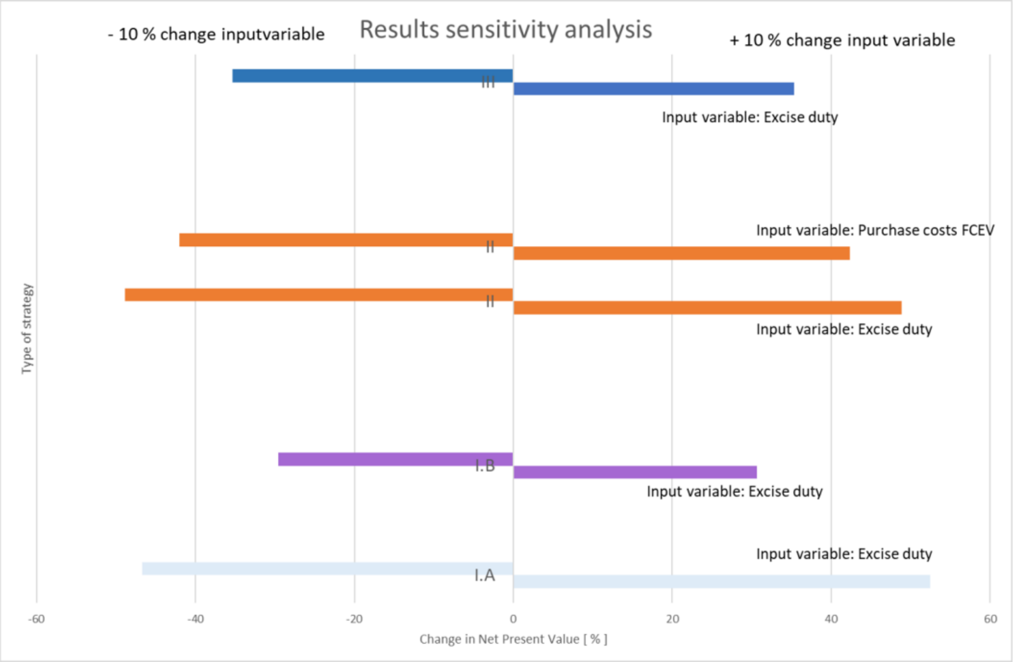


Figure 31. Results of the sensitivity analysis

7. Discussion

Based on the scenario and sensitivity analysis executed in chapter 6, a reflection is made on the validity of the research considering the literature review and the model. Thereafter, the limitations of the research are mentioned. Subsequently, recommendations are made for further research and recommendations are made to the Dutch government and the Port Authority of Rotterdam.

7.1 Validity

The factors that are perceived as highly uncertain and have a high influence on the results in the social cost-benefit analysis are the environmental price of CO2-emissions and the availability of green hydrogen. Both factors have a negative influence on the net present value of strategy II. Both factors show that the Net Present Value of strategy II might be overestimated.

Other included factors in the model are either perceived as less uncertain or of less influence.

The model is validated, since a sensitivity analysis of the input variables is addressed. It is shown that how sensitive the model is to changes of certain input variables. The sensitivity analysis show intuitive results. Therefore, it is plausible that the SCBA does not have big errors.

7.2 Limitations of the performed research

The performed research knows several limitations. The limitations that are identified are divided into the execution of the research, the scope and assumptions and data accessibility. When the results are interpreted, it is important to reflect on the limitations faced during the research.

7.2.1 Execution of the research

For the study two literature reviews were executed. The articles found were based on several factors. To find the most promising energy carriers the articles of the first literature review were consulted. However, some articles had a more dominant role in the review than other articles. The article of Tol et al (2023) plays a large role for the determination of the most promising energy carriers and the policy recommendation document of Fabius et al. (2020) plays a dominant role for the forecasts for the uptake of the energy carriers in the Netherlands without strategic interventions. This could have influenced the results of the research. In the report of Noordijk et al. (2020) a higher uptake of battery electric vehicles was predicted through market forces. The subsidy required would be lower in this case for strategy I.A and I.B. This implies that the Net Present Values of strategy I.A and I.B might have been underestimated.

There are also several studies included that from 2015 to 2020, like the article of Bateman et al (2018) and the Wuppertal studies of Lechtenböhmer et al. (2018) and Pastowski (2017), since technological developments and corresponding knowledge develop rapidly, it could be questionable if the knowledge retrieved from these sources is still valid.

Based on the additional literature review it is determined which costs and the benefits are included in the social costs-benefit analysis. However, no article was found in the online TU Delft Library in which both the social cost-benefit analysis and heavy-duty transport were addressed. The costs and the benefits included were determined on similarities with other articles or by analytical thinking. However, this could have led to a more arbitrary inclusion of the costs and benefits.

By the use of a social cost-benefit analysis, only the social-welfare perspective is taken into consideration. By the analysis only the socio-economic feasibility is investigated. Potential more technical feasibility limitations are solely addressed qualitatively in the literature review. For example, barriers for recharging of battery electric vehicles are identified for the grid reinforcement or grid congestion. Furthermore, the social-welfare perspective comprises a wide perspective for many involved parties. It is unidentified if governmental parties can afford the high expenditures to enable the transition in the heavy-duty segment.

A constraint of the social cost-benefit analysis in general is that some effects that are included cannot be measured or monetized. Especially if these are considered as main effects, the social cost-benefit analysis can be less relevant and less trustworthy. Also the effects that are expressed by using people's willingness to pay for the provisioning or prevention of goods or services can be arbitrary as stated by Renes and Romijn (2013). For the case study, the valuation of the (avoided) emissions are based on the figures of Klein et al. (2020) and de Bruyn et al., (2023). However, it could be that through more or less economic welfare or urgency regarding the climate crisis this valuation might be different.

7.2.2 Scope choices and assumptions

For the scope, several choices are made. Only the Rotterdam – Duisburg corridor is considered. Thus, solely the socio-economic effects for one corridor are assessed in the social cost-benefit analysis. For infrastructure investments, it would be preferable to regard the corridors on a European scale as stated by Pastowski (2017). It is questionable what implications this has on the strategies. However, since most of the road transport takes place in continental areas, it is desirable to gain insights on European scale.

In the social cost-benefit analysis, the tank-to-wheel scope was chosen for costs and benefits for stimulating the purchase of the zero-emission vehicles, the corresponding infrastructure and the tax on fossil fuels. This scope could result in the fact that the costs and/or benefits are shifted to another part of the chain, taking a well-to-wheel perspective as shown in figure 32.

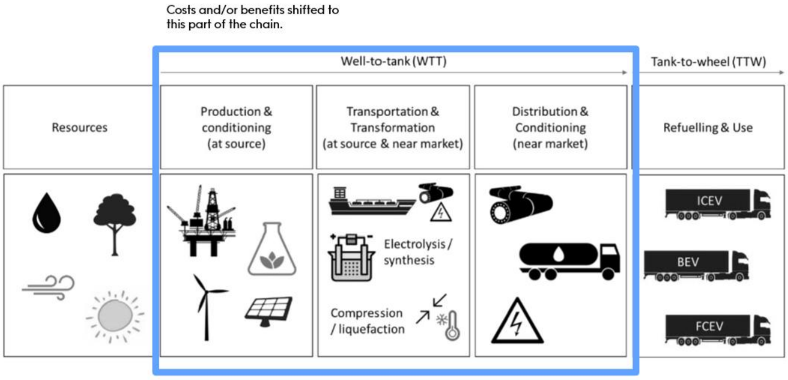


Figure 32. Costs or benefits shift to another part of the chain

Note I. Taken from "The potential of e-fuels for heavy-duty road transport in the Netherlands," by Tol, D., Verbeek, M.M.J.F., Gaggar, S., Hulsbosch-Dam, C.E.C., Vredeveldt, A.W., van Zyl, P.S., van Ark E.J., Paschinger, P., Smokers, R.T.M. (2023). TNO, p.24, Available at Smartport.nl
Note II. The colored block is added to clarify how the costs can be shifted in the chain.

For example, for e-fuels the production and conditioning process at the source would require high capital expenditures, especially in the direct air capture technology. The high expenditures on the production side would imply that the Net Present Value is overestimated. However, if economies of scale could be enabled in the production of e-diesel as stated in the study of Prussi et al. (2022), the expenditures would be reduced. For the strategy in which hydrogen is promoted, the building of the distribution pipelines and conditioning facility would also have high expenditures, since this infrastructure does not yet exist according to Tol et al. (2022). This would mean that the Net Present Value of strategy II is overestimated.

For strategy I.A, I.B. and II a subsidy is provided. This is to some extent hypothetical, since this budget must be available by either the European Union or the Dutch government for the transition in the heavy-duty road segment.

In the social cost-benefit analysis, the benefits of smaller batteries, reduced time losses for charging and differences in electricity costs are not taken into account. This might result in other outcomes for strategy I.B in which the catenary electric road system is stimulated.

The tariffs for renewable electricity, for hydrogen and for e-diesel are indirectly qualitatively considered, since they are included in the total cost of ownership. However, the tariffs of the energy carriers as a more explicit cost or benefit are not included in the SCBA, otherwise there would be a double counting. The tariffs of hydrogen and e-diesel also might be different in maritime ports, if the production process would take place in the port areas. These uncertainties are not included in the uncertainty analysis.

Last, the social cost-benefit analysis disregards the subsidies that are already provided by the Dutch government. Therefore, the Net Present Value of strategy I.A, I.B and II might be overestimated

7.2.3 Data availability

The data is obtained from different articles and policy documents. There was limited data available and therefore assumptions were made that could be discussible. The amount of stations, recharging and hydrogen refuelling, are identified on Google Maps (n.d.). It could easily be that one of the stations along the corridor is missed. It also remains unknown if these identified stations welcome heavy-duty vehicles. Through personal contact with the company FastNed referred to as Blauuw, personal communication (2023), it is known that currently vehicles heavier than 7.5 tons are not welcome at the stations. Mainly due to safety reasons related to passenger vehicles. In addition, at the older (arch) stations it is not possible to get to the station with a high vehicle (max. 2.75 m). FastNed is currently investigating which locations might already be suitable for > 7.5-tonne vehicles and which locations require adjustments and what exactly needs to be adjusted. However, in the study it is assumed that the subsidy stimulated the building of new recharging stations by covering 50 % of the costs. In case only small adaptations are required to the recharging stations, the amount of subsidy could be overestimated.

The hydrogen station operators were also approached, but did not respond to the question if the heavy-duty vehicles are welcome at the moment. Similar to the recharging stations, in this study it is assumed that the subsidy stimulated the building of new hydrogen stations by covering 50 % of the costs. The amount of subsidy could therefore be overestimated, in case only small adaptations are required.

The developments for e-diesel considering the emissions emitted from a well-to-wheel perspective, also remain uncertain. Bosteels, et al. (2022) and Van Kranenburg et al. (2020) states that e-diesel has the potential to become carbon neutral from a well-to-wheel perspective.

However, current figures of Klein et al. (2020) and Gustafsson et al. (2021), show higher values for the well-to-wheel emissions of e-diesel.

7.3 Recommendations for further research

Considering the scientific relevance, the validity and the limitations of the research, the following recommendations are made for further research. First, it would be recommendable to further analyze the potential feasibility of decarbonizing the heavy-duty fleet on a European scale. In this research solely the Rotterdam – Duisburg corridor is considered. Larger financial support could be provided on European scale and since road transport is mainly organized continental, it would be valuable to investigate the European-wide road network.

By making a social cost-benefit analysis, indirectly the socio-economic welfare perspective is chosen. This makes some relevant technical barriers are left out of scope, like the feasibility on the grid reinforcement and potential net congestion. It would be interesting to investigate the feasibility or the level of limited availability of electricity on the grid for the recharging of the heavy-duty vehicles in different areas. Furthermore, in the literature review it was also found that there is limited availability of raw materials to make batteries (Tol et al., 2023). It could also be interesting to investigate how this potential limited availability would affect the transition in the heavy-duty segment.

It is advised to do further research on the costs and the benefits from a well-to-tank perspective. This includes the costs for production and conditioning at the source, transportation and transformation at the source and near the market (like electrolysis and synthesis, compression and liquefication) and last distribution and conditioning near the market. The developments go rapidly and the expenditures of these processes can be high. It could be interesting to examine if by a similar amount of subsidy at the production side, the transition could be accelerated for e-diesel and hydrogen. Thus, if the emissions from a well-to-wheel perspective could be decreased for hydrogen and e-diesel and what the costs are.

Furthermore, it is recommend to do further research on the (future) tariffs of diesel, electricity, hydrogen and e-diesel and how this affects social-welfare. The tariffs could have a high level of influence on the decision of road transport companies to make a transition to a specific energy carrier. For further research the development and the level of uncertainty could be addressed. It is also worth knowing what the influence of maritime ports is on the tariffs due to their ideal place for production of the energy carriers.

Last, it would be worth knowing if there are additional benefits that the catenary electric road system causes. These additional benefits could be through reduced time losses by dynamic charging, lower electricity costs and lower battery electric vehicle costs since smaller batteries are necessary.

7.4 Recommendations to the Port Authority and the Dutch government

The European Union, the Dutch government and the Port Authority provided an unclear direction considering energy carriers and technologies in their current (proposed) policies and strategy. Both driving electric and hydrogen were promoted through subsidy or obligation. It would be recommendable to align the policies and strategy to avoid sunk costs and to give a more clear direction to the road transport companies and system operators. In addition, it is important that the infrastructure of the road network and thus the infrastructure of the hinterland of maritime ports and the port are aligned. Mainly because of the accessibility of the port to the hinterland in order to retain its competitive position as a transit node.

For the Dutch government it is also recommended to monitor the high expenditures for subsidies and the severe losses of tax on fossil fuels. It could be that a combination of these expenditures and losses are unaffordable for the government.

It is also advised to make the usage of zero-emission vehicles mandatory from a certain time and to announce this forehand. This obligation is required to meet the climate target of zero-emission in 2050, with only stimulation through subsidy this target will not be achieved.

It is further recommended to the Dutch government and the Port Authority to keep on track with the future developments of renewable electricity, green hydrogen and zero-emission e-diesel from a well-to-wheel perspective. If these production processes are not zero-emission, it is questionable to promote the energy carrier.

Last, other concerns arise if battery electric vehicles get a large uptake. The risk for limited grid reinforcement, grid congestion and the limited availability for materials of the batteries (Tol et al., 2023). These risks could cause potential difficulties for driving electric in the future. It is recommend to monitor these risks to counter future barriers.

8. Conclusions and contributions

In this chapter first an explicit answer is provided on the main research question based on the findings of all sub questions that were provided in chapter 3 to 7. After, a reflection is made of the contribution of scientific knowledge for which the knowledge gap is addressed. Last, the more practical societal contribution is reflected on, for which the practical problem statement is addressed.

8.1 Explicit answer to the main research question

In this section an explicit answer is provided on the main question; *What is the socio-economic feasibility of strategies to decarbonize heavy-duty road freight transport in the hinterland of maritime ports towards 2050?*

The socio-economic feasibility was determined by strategies in which the promising energy carriers and corresponding technologies were stimulated by subsidy or made mandatory in the hinterland of maritime ports. The strategies were made with promising energy carriers and corresponding technologies to decarbonize heavy-duty road transport found in the literature review and stated as follows:

Strategy I.A. Subsidy for battery electric heavy-duty vehicles and recharging stations that use renewable electricity.
Strategy I.B. Subsidy for battery electric heavy-duty vehicles with a pantograph system and recharging stations that use renewable electricity + realization of a catenary electric road system.
Strategy II. Subsidy for fuel cell electric heavy-duty vehicles and hydrogen refueling stations in which green gaseous hydrogen is used.
Strategy III. Making the usage of e-diesel mandatory in conventional heavy-duty vehicles with an internal combustion engine.

For the determination of the socio-economic feasibility a social-cost benefit analysis was made. Based on the social cost-benefit analysis, it can be concluded that all proposed strategies would not be welfare enhancing towards 2050. Considering their socio-economic feasibility, all strategies are undesirable compared to the zero-alternative if no actions are taken. From a social-welfare perspective, the costs outweigh the benefits even with the environmental benefits included at the current environmental prices. If the environmental prices would rise because of higher urgency to reach the climate target strategy, the strategies could become welfare enhancing.

For all proposed strategies the climate targets are not reached by the considered fleet from a well-to-wheel perspective. The carbon emissions are reduced by 30 % - 50 % compared to the zero-alternative. Since it is not made mandatory to drive with zero-emission vehicles, in strategy I.A, I.B and II a percentage the fleet remains driving on a blended mix of diesel + biodiesel. It could be that road transport companies and station operators were not incentivized enough to contribute to the transition. For strategy III, the production process of e-diesel still causes carbon emissions. Besides, severe losses for society would occur if the tax on fossil fuel cannot be maintained. This would be the case if zero-emission vehicles have a large uptake. This loss of the tax on fossil fuel is mainly a cost for the government. The subsidy in strategy I.A, I.B and II are also a cost for the Dutch government, while the benefits reflected in the increase in producer-surplus are received by private parties. It could be questionable if it is feasible that the government is able to pay these high expenditures to enable the transition.

Even though all proposed strategies are unfeasible from a socio-economic welfare perspective at the current environmental prices, it can be concluded that some strategies are more desirable than other strategies. From a social-economic welfare perspective, it would be the most feasible to stimulate battery electric vehicles and recharging stations by subsidy for decarbonizing heavy-duty road transport in the hinterland of maritime ports. This is based on the net present value results of a social cost-benefit analysis, taking the current CO_2-price of 130 euro per ton. At a CO_2-price of 500 euro per ton, the Net Present Value of strategy I would be higher than 1. This implies from this carbon-price, strategy I would be welfare enhancing.

A carbon emissions reduction of 50 % in 2050 is reached in strategy I compared to the zero-alternative. The carbon emission that are still emitted are caused by the 25 % of the considered fleet that still drives on a blended mix of diesel and biodiesel, since zero-emission transport is not made mandatory. After 2025, a strong decrease of carbon emissions can be seen. This is mainly because renewable electricity from either solar, wind or biomass will be available after 2025 (CBS, 2023). Compared to stimulating fuel cell electric vehicles through subsidies, a lower level of subsidy is required for the same percentage of additional users of the subsidy. This is due to the lower purchase costs of the battery electric vehicles than the fuel cell electric vehicles (Tol et al., 2023). In addition, the environmental benefits of strategy I are higher than the environmental benefits of strategy II. This is a result of the later availability of green hydrogen in 2030 than the renewable electricity in 2025 (Sens et al., 2022; Tol et al., 2023; CBS, 2023). The results of the SCBA show that strategy II stimulates the purchase of fuel cell electric vehicles too early. From 2025 until 2030, grey hydrogen needs to be used by the fuel cell electric vehicles. This results in a peak of carbon emissions between 2025 and 2030. It would be more desirable to stimulate the purchase of fuel cell electric vehicles after 2030, when green hydrogen is available.

Based on the literature review, the catenary electric road system can be perceived as promising technology. However, from a socio-economic welfare perspective it would be undesirable to stimulate the construction of the system through subsidy at the current environmental prices. The strategy would become welfare enhancing at a CO_2-price of 800 euro per ton. Since the highest level of subsidy needs to be provided in order to stimulate the purchase of the pantograph system for road transport companies and to stimulate the building of the catenary electric road system by a system operator. Furthermore, there are no additional environmental benefits from a well-to-wheel perspective compared to only stimulating battery electric vehicles and recharging stations, because the same battery electric vehicles are used with the same characteristics.

E-diesel was perceived as a promising energy carrier based on the literature review. However, the socio-economic feasibility study shows that making the usage mandatory is undesirable. The overall environmental benefits for e-diesel from a well-to-wheel perspective are lower compared to all other proposed strategies. Making the use of e-diesel mandatory from 2040 is thus not an effective strategy for reaching the climate targets for CO_2-reduction given the current data about the well-to-wheel emissions for e-diesel. The advantages of that there is no subsidy required for since this the current fleet and infrastructure can be used do not outweigh the environmental costs. What can be learnt from the strategy is by making an energy carrier mandatory more rapidly a shift takes place. In order to meet the climate targets, making ze-emission transport mandatory might contribute to achieving the climate targets.

8.2 Contribution to scientific knowledge

In the introduction of this thesis, the knowledge gap was stated as follows: *A social cost-benefit analysis that assesses social-economic welfare effects of energy carriers to decarbonize heavy-duty road transport in the hinterland of maritime ports remains unaddressed in the literature.*

This study fulfills the knowledge gap by making a social cost-benefit analysis that assesses the social-economic welfare effects of strategies in which energy carriers to decarbonize heavy-duty road transport are stimulated by subsidy or for which the usage is made obligatory. Several energy carriers were included in the SCBA that were found to be promising in the literature review. The literature review gives an overview of many energy carriers. The energy carriers included in the SCBA were promising considering factors like financial and technological, but also the production process and the availability of infrastructure are regarded. Furthermore, the factors are considered on their development throughout time and put in a timeline. The study made a contribution to scientific knowledge by integrating the development over time of these factors in the strategies and indirectly thus in the SCBA.

This study also provides insights on the following social-economic welfare effects: the change in producer-surplus, external effects (e.g. less CO_2 emissions), the fuel tax losses and the societal costs, consisting of the subsidy.

It is interesting that even though mainly a transport perspective is taken, which comprises refueling and usage (also named tank-to-wheel perspective), that the whole chain from production starting is taken into account (the wheel-to-wheel perspective) for the consideration of the emissions. Therefore, a reflection is made on the fact that the emissions are not shifted to another part of the chain. In the SCBA this consideration is seen in the environmental benefits. This makes the study take a really broad scope.

The advantages of maritime ports through the proximity of the production process of (green) hydrogen, e-diesel and renewable electricity are also taken into consideration in this study. These energy carriers could be used in the heavy-duty road segment and the tariffs of the energy carriers could be reduced in maritime ports because of their advantages. This is considered in the uncertainty analysis.

The results of the SCBA also contribute to scientific knowledge. The stimulation of battery electric vehicles shows the highest Net Present Value. Mainly due to the most effective subsidy. A large amount of the fleet can make a transition due to the low purchase costs of battery electric vehicles. The environmental benefits are the largest, due to early availability of renewable electricity from 2025.

8.3 Contribution to societal challenge

The following practical problem statement was introduced in chapter one: *Policymakers and strategists of the Port Authority have a lack of knowledge to decarbonize heavy-duty transportation in the hinterland, without deteriorating the competitive position of a maritime port as a transit node.*

In this study policymakers and strategists of port authorities gain insight on the strategic interventions that could contribute for decarbonizing heavy-duty road freight and remaining reliable, profitable and accessible as a transit node. The study shows how the most promising energy carriers can be integrated into strategies. The strategies are made as realistic as possible considering proposed and current legislation and policies of the European Union, the Dutch government, the Dutch Tax Authority, Rijkswaterstaat and the Port Authority of Rotterdam. The technological and financial development of the energy carriers and the corresponding technologies throughout time are taken into account in the strategies. The availability of the infrastructure and the energy carriers are also integrated in the strategies. These considerations ensure that the proposed strategies in this study are practical.

The study shows that all proposed strategies to enable the transition in the heavy-duty segment are not welfare enhancing, which is intuitive since it is plausible that the transition would already happen without interventions through market forces otherwise. If the environmental prices would increase in case of more urgency for achieving the climate targets, the interventions would be welfare enhancing.

The study provides insights into the severe costs for governmental institutions to enable the transition. There are severe losses of the tax on fossil fuels that cannot be maintained in case of a large uptake of zero-emission vehicles. In addition, the subsidy to stimulate zero-emission techniques are also high expenditures for the government. As the strategies were proposed in this study, the benefits are mainly for the public parties like the road transport companies and station operators through the increase in utility that they receive through the subsidy, in jargon: increase in producer-surplus. The environmental benefits that the strategies cause are perceived as benefits for society as a whole.

In addition, the study also provides insights between the difference of mandatory and stimulation by subsidy. A stricter strategy in which an energy carrier is made mandatory shows a rapid change in the fleet and therefore also in the polluted emissions and the environmental benefits/costs. Making zero-emissions heavy-duty vehicles mandatory could contribute to achieving the climate targets of zero-emission in 2050.

Based on the findings of the study, it can be concluded that stimulated battery electric vehicles and infrastructure by subsidy as a strategy would currently be the most socio-economic feasible intervention. Mainly due to the highest environmental benefits because of the availability of renewable electricity from 2025 and the largest number of zero-emission vehicles that can be purchased with the available subsidy. However, climate targets of zero-emission will still not be achieved by 50 %. Stimulating hydrogen would result in less zero-emission vehicles in comparison to the stimulation of battery electric vehicles, due to the higher purchase costs of fuel cell electric vehicles. It will also result in less environmental benefits, because green hydrogen would only be available after 2030.

The competitive position for a maritime port as a transit node will not be lost if the demand and supply of the energy carrier are equivalent, this supports the reliability and the profitability of a port. Furthermore, the provisioning of the infrastructure suited for the sustainable energy carrier must be in place in the port area to remain accessible. The Alternative Fuel Infrastructure Regulation proposed by the European Union already provides some direction regarding the provisioning of infrastructure in the hinterland, this also supports the accessibility of road transport of maritime ports indirectly. This legislation also counters the chicken-egg problem that there is no infrastructure but only vehicles.

All these insights contribute to the knowledge of policymakers of the Dutch government and strategists of the Port Authority of Rotterdam and can be integrated into their policies and strategy.

References

Ainalis, D. T., Thorne, C. and Cebon, D. (2020) *White Paper: Decarbonising the UK 's Long-Haul Road Freight at Minimum Economic Cost. Technical Report CUED/C-SRF/TR17.* Cambridge, UK: Centre for Sustainable Road Freight. Available at: http://www.csrf.ac.uk/wpcontent/uploads/2020/07/SRF-WP-UKEMS-v2.pdf.

Ajanovic, A., & Haas, R. (2021). Renewable energy systems implementation in road transport: prospects and impediments. *Renewable Energy and Environmental Sustainability,* 6, 39.

Annema, J. A. & Van Wee, B. (2021). *Verbeteren van het transportsysteem.* Hoe om te gaan met financiële instrumenten in je MKBA?

Archief Locaties - H2Platform. (n.d.). H2Platform. https://opwegmetwaterstof.nl/tanklocaties/

Bateman, D., Leal, D., Reeves, S., Emre, M., Stark, L., Ognissanto, F., Myers, R. & Lamb, M. (2018). *Electric road systems: A solution for the future?* (No. 2018SP04EN). Paris: World Road Association (PIARC).

Belastingdienst. (2023a). *Tarief bzm*. https://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/prive/auto_en_vervoer/belastingen_op_auto_en_motor/belasting_zware_motorrijtuigen/tarief_bzm

Belastingdienst. (2023b). *Tarievenlijst Accijns en verbruiksbelastingen*. https://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/themaoverstijgend/brochures_en_publicaties/tarievenlijst_accijns_en_verbruiksbelastingen

Blauuw, T., personal communication, (March 22, 2023). FastNed.

Bosteels, D., Villafuerte, P. M., Demuynck, J., Wilkes, T., Chaillou, C., & Hultman, M. (2022). Combination of advanced emission control technologies and sustainable renewable fuels on a long-haul demonstrator truck. SIA Powertrain & Energy.

de Boer, L. E., Mouter, N., & de Vries, M. O. (2022). Brede welvaart heeft ethische blik nodig Bijdrage aan het Colloquium Vervoersplanologisch Speurwerk 13 en 14 oktober 2022, Utrecht. In *Brede welvaart heeft ethische blik nodig: Bijdrage aan het Colloquium Vervoersplanologisch Speurwerk 13 en 14 oktober 2022, Utrecht.*

de Bruyn, S., de Vries, J., Juijn, D., Bijleveld, M., van der Giesen, C., Korteland, M., van Santen, W., Pápai, S. (2023). *Handboek Milieuprijzen 2023.*https://ce.nl/wp-content/uploads/2023/03/CE_Delft_220175_Handboek_Milieuprijzen_2023_DEF.pdf

Centraal Bureau voor de Statistiek. (2018). *Helft goederen uit Rotterdam gaat door naar buitenland.* Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/nieuws/2018/36/helft-goederen-uit-rotterdam-gaat-door-naar-buitenland

Centraal Bureau voor de Statistiek. (2023). Aandeel Hernieuwbare Elektriciteit met 20 procent gestegen in 2022. Centraal Bureau voor de Statistiek. https://www.cbs.nl/nl-nl/nieuws/2023/10/aandeel-hernieuwbare-elektriciteit-met-20-procent-gestegen-in-2022

Centraal Bureau voor de Statistiek. (n.d.). *Hoeveel zware vrachtvoertuigen zijn er in Nederland?* Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/vervoermiddelen-en-infrastructuur/vrachtvoertuigen

Corporate Finance Institute. (2022). *Benefit-Cost Ratio (BCR).* https://corporatefinanceinstitute.com/resources/accounting/benefit-cost-ratio-bcr

Cunanan, C., Tran, M. K., Lee, Y., Kwok, S., Leung, V., & Fowler, M. (2021). A review of heavy-duty vehicle powertrain technologies: Diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. *Clean Technologies*, *3*(2), 474-489.

Dimitriou, P., & Javaid, R. (2020). A review of ammonia as a compression ignition engine fuel. *International Journal of Hydrogen Energy*, 7098-7118.

Fabius, B., van Sloten, R., & Aldenkamp, M (2020). *Transitiestudie verduurzaming wegtransport.* EVConsult. rijksoverheid.nl.

Frank, J., Brown, T., Ha, H., Slade, D., Haverly, M., & Malmsheimer, R. (2022). Quantifying and comparing the cumulative greenhouse gas emissions and financial viability of heavy-duty transportation pathways for the Northeastern, United States. *Fuel*, *323*, 124243.

Gaspars-Wieloch, H. (2019). Project net present value estimation under uncertainty. *Central European Journal of Operations Research*, *27*(1), 179-197.

GeoWeb 5.5 (n.d.). https://maps.rijkswaterstaat.nl/gwproj55/index.html?viewer=Inweva.Webviewer

Google Maps (n.d.). https://www.google.nl/maps/dir/Maasvlakte+Rotterdam/Duisburg,+Duitsland/Air+Liquide,+Groene+Kruisweg,+Rhoon/@51.7013545,4.8260364,9z/data=!3m1!4b1!4m20!4m19!1m5!1m1!1s0x47c5ab5157b8a7d3:0x15ceb7ebdc9d7515!2m2!1d4.031126!2d51.9632789!1m5!1m1!1s0x47b8bef5a58b273b:0x427f281315473c0!2m2!1d6.7623293!2d51.4344079!1m5!1m1!1s0x47c4343c8d10f715:0x7b488b02571f27e7!2m2!1d4.4372666!2d51.865984!3e0

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., & Murphy, J. D. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy*, *1*, 100008.

Gustafsson, M., Svensson, N., Eklund, M., Öberg, J. D., & Vehabovic, A. (2021). Well-to-wheel greenhouse gas emissions of heavy-duty transports: Influence of electricity carbon intensity. *Transportation Research Part D: Transport and Environment*, *93*, 102757.

Jalali, S., & Wohlin, C. (2012, September). Systematic literature studies: database searches vs. backward snowballing. In *Proceedings of the ACM-IEEE international symposium on Empirical software engineering and measurement* (pp. 29-38).

Klein, A., Hilster, D., Scholten, P., van Wijngaarden, L., Tol, E., Otten, M. (2020). STREAM goederenvervoer 2020. *Delft, CE Delft.*

Lechtenböhmer, S., Schostok, D., Kobiela, G., Knoop, K., Pastowski, A., & Heck, S. (2018). *Deep decarbonisation pathways for transport and logistics related to the Port of Rotterdam: PoR transport; synthesis report.*

Lopatin, O. P. (2020, August). Development of a methodology for assessing the impact of vehicles on the acoustic environment. In *IOP Conference Series: Earth and Environmental Science* (Vol. 548, No. 6, p. 062049). IOP Publishing.

Ministerie van Algemene Zaken. (2022a). *Voorbereiding invoering vrachtwagenheffing*. Goederenvervoer | Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/goederenvervoer/vrachtwagenheffing#:~:text=Het%20kabinet%20werkt%20aan%20de,gebruik%20van%20de%20Nederlandse%20wegen.

Ministerie van Algemene Zaken. (2022b). *Wanneer en hoe betaal ik accijns?* Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/belasting-betalen/vraag-en-antwoord/accijns-betalen#:~:text=Het%20kabinet%20heeft%20de%20accijns,11%2C1%20cent%20per%20liter.

Ministerie van Algemene Zaken. (2023). *Wat is de maximumsnelheid voor auto's op de snelweg?* Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/verkeersregels/vraag-en-antwoord/wat-is-de-maximumsnelheid-voor-auto-s-op-de-snelweg

Ministerie van Economische Zaken en Klimaat. (2019). *Biobrandstoffen*. Milieuvriendelijke Brandstoffen Voor Vervoer | Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/milieuvriendelijke-brandstoffen-voor-vervoer/biobrandstoffen

Ministerie van Financiën. (2020). *Rapport Werkgroep discontovoet 2020*. https://open.overheid.nl/documenten/ronl-d985cdc5-5da7-4644-be09-4c22bfa885be/pdf.

Ministerie van Infrastructuur en Waterstaat. (2020a). *Internetconsultatie Vrachtwagenheffing*. eerstekamer.nl. https://www.eerstekamer.nl/wetsvoorstel/35910_wet_vrachtwagenheffing

Ministerie van Infrastructuur en Waterstaat. (2022a). *Kabinet investeert in meer waterstoftankstations*. Nieuwsbericht | Rijksoverheid.nl. https://www.rijksoverheid.nl/actueel/nieuws/2022/11/22/kabinet-investeert-in-meer-waterstoftankstations

Ministerie van Infrastructuur en Waterstaat. (2022b). Ook vrachtwagens op de schone toer. Nieuwsbericht | Rijksoverheid.nl. https://www.rijksoverheid.nl/actueel/nieuws/2022/04/25/ook-vrachtwagens-op-de-schone-toer

Ministerie van Infrastructuur en Waterstaat. (2022c). *Wat is er wettelijk geregeld voor de rijtijden en rusttijden bij wegvervoer?* Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/werktijden/vraag-en-antwoord/rijtijden-en-rusttijden-wegvervoer#:~:text=De%20maximale%20ononderbroken%20rijtijd%20mag,duurt%20dan%20minimaal%2015%20minuten

MPG to Km/l Converter. (n.d.). https://www.mpgtolitres.com/mpg-to-kml

Mouter, N. (2012). Voordelen en nadelen van de Maatschappelijke Kosten-en Baten analyse nader uitgewerkt. In *Colloquium Vervoersplanologisch Speurwerk 2012, Amsterdam, 22-23 november 2012*. Stichting Colloquium Vervoersplanologisch Speurwerk (CVS).

Mouter, N. (2014). Cost-benefit analysis in practice.

Mouter, N. (2021). New methods, reflections and application domains in transport appraisal. Academic Press.

Mouter, N., Cabral, M. O., Dekker, T., & van Cranenburgh, S. (2019). The value of travel time, noise pollution, recreation and biodiversity: A social choice valuation perspective. *Research in Transportation Economics*, *76*, 100733.

Netherlands Enterprise Agency. (2022). *Electric Vehicles Statistics in the Netherlands*. https://www.rvo.nl/sites/default/files/2022-09/Statistics-elektric-vehicles-and-charging-in-the-Netherlands-up-to-and-including-August-2022.pdf. https://rvo.nl

Noordijk, R., Refa, N., & Van Rookhuijzen, J. (2020). *Truckers komen op stroom*. https://elaad.nl/publicaties/. https://elaad.nl/publicaties/

Nykvist, B., & Olsson, O. (2021). The feasibility of heavy battery electric trucks. *Joule*, *5*(4), 901-913.

Overheid (n.d.). *Conceptwetsvoorstel voor internetconsultatie*. Overheid.nl | Consultatie Wet Vrachtwagenheffing.. https://www.internetconsultatie.nl/wet_vrachtwagenheffing

Pallas, M. A., Kennedy, J., Walker, I., Chatagnon, R., Berengier, M., & Lelong, J. (2015). *Noise emission of electric and hybrid electric vehicles: deliverable FOREVER (n° Forever WP2_D2-1-V4)* (Doctoral dissertation, IFSTTAR-Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux).

Panoutsou, C., Germer, S., Karka, P., Papadokostantakis, S., Kroyan, Y., Wojcieszyk, M., Maniatis, K., Marchand, P. & Landalv, I. (2021). Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake. *Energy Strategy Reviews*, 34, 100633.

Parviziomran, E., & Bergqvist, R. (2023). A cost analysis of decarbonizing the heavy-duty road transport sector. Transportation Research Part D: *Transport and Environment, 120*, 103751.

Pastowski, A. (2017). *Technologies and fuels for decarbonising maritime and hinterland freight transport: background report.* Port of Rotterdam & Wuppertal Institute

Plötz, P. (2022) “Hydrogen technology is unlikely to play a major role in sustainable road transport.” *Nat Electron* 5, 8–10 doi: 10.1038/s41928-021-00706-6

Plötz, P., Wachsmuth, J., Sprei, F., Gnann, T., Speth, D., Neuner, F., & Link, S. (2023). Greenhouse gas emission budgets and policies for zero-Carbon road transport in Europe. Working Paper Sustainability and Innovation, No. S02/2023, Fraunhofer-Institut für System- und Innovations Forschung ISI, Karlsruhe, https://doi.org/10.24406/publica-975

Port of Rotterdam (2022a). *Projectopdracht; truckparking Waalhaven, Antonie Bodaanweg* ((Internal use only)) -

Port of Rotterdam (2022b). *Projectontwikkelplan - WEH-Bodaanweg, E-laadplein truckparking.* - ((Internal use only)) –

Port of Rotterdam (n.d.-a). *Improving the port of Rotterdam hinterland accessibility and transport supply chain.* portofrotterdam.com

Port of Rotterdam (n.d.-b). *Wegtransport.* https://www.portofrotterdam.com/nl/logistiek/verbindingen/intermodaal-transport/wegtransport

Prussi, M., Laveneziana, L., Testa, L., & Chiaramonti, D. (2022). Comparing e-Fuels and Electrification for Decarbonization of Heavy-Duty Transports. *Energies*, *15*(21), 8075.

Renes, G. & Romijn, G. (2013). *Algemene leidraad voor maatschappelijke kostenbatenanalyse.* Centraal Planbureau. cpb-pbl-boek-10-algemene-leidraad-voor-maatschappelijke-kostenbatenanalyse.pdf

Rijkswaterstaat. (2021). *Richtlijn Ontwerp Autosnelwegen Veilige Inrichting van Bermen*. Rijkswaterstaat Grote Projecten en Onderhoud

Samadi, S., Lechtenböhmer, S., Schneider, C., Arnold, K., Fischedick, M., Schüwer, D., & Pastowski, A. (2017). *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam.* Wuppertal, Germany: Wuppertal Institute for Climate, Environment and Energy.

Samadi, S., Schneider, C. & Lechtenböhmer, S. (2018). *Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam*. Wuppertal Institute.

Sen, B., Ercan, T., & Tatari, O. (2017). Does a battery-electric truck make a difference?–Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. *Journal of cleaner production*, *141*, 110-121.

Sens, L., Neuling, U., Wilbrand, K., & Kaltschmitt, M. (2022). Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050–A techno-economic well-to-tank assessment of various supply chains. International Journal of Hydrogen Energy.

Tol, D., Gaggar, S., Verbeek, M. (2022). *Need for public electricity and hydrogen distribution infrastructure for heavy duty road vehicles in the port of Rotterdam.* TNO. –(Internal use of the Port Authority only)-

Tol, D., Verbeek, M.M.J.F., Gaggar, S., Hulsbosch-Dam, C.E.C., Vredeveldt, A.W., van Zyl, P.S., van Ark E.J., Paschinger, P., Smokers, R.T.M. (2023). *The potential of e-fuels for heavy duty road transport in the Netherlands.* TNO. Available at Smartport.nl

Transport Guide Rotterdam (n.d.) *Road transport Companies.* https://www.transportguiderotterdam.com/road-transport-s0

Van Kranenburg, K., et al (2020) E-fuels: towards a more sustainable future for truck transport,shipping and aviation. TNO report

Voskamp, A. & Dodemont, B. (2022). *Uitrolstrategie laadinfrastructuur voor trucks in de haven.* Port of Rotterdam - ((Internal use only)) –

Wiegmans, B., Mouter, N., Vanelslander, T., & Verweij, S. (2022). *Public-Private Partnerships in Port Areas: Lessons Learned from Case Studies in Antwerp and Rotterdam* (pp. 107-128). Springer International Publishing.

Appendices

A. Strategy of the Port Authority

Strategy of the Port of Rotterdam regarding the transition for transportation by trucks

"Although Port of Rotterdam has decided to invest in recharging stations in the Rotterdam port area, the other strategies for decarbonizing road transport are also considered. The Port of Rotterdam and it's Strategy and Analysis department highly values the review of different strategies albeit having invested in certain technologies already." – Pieter de Waard, Corporate Strategist at the Port of Rotterdam.

TNO made a forecast for the Port of Rotterdam, which stated that an uptake of e-trucks can be expected on the short term for heavy-duty truck transportation (Tol et al., 2022). Subsequently, this led to the roll-out strategy, determined internally, in which the Port focuses on public charging plazas at truck parks. During the night trucks could make use of slow-charging and during the day fast-charging. As owner of truck parks, the Port will assist in the facilitation of the charging point, but will not exploit the service. The service will be exploited by Truckparking Rotterdam Exploitatie BV (Port of Rotterdam, 2022a).

At the moment no public charging points for heavy-duty trucks are available. However, three locations are considered as potential locations; Truckparking Maasvlakte Plaza, de Botlek and Antoine Bodaanweg. For Bodaanweg, located in the Waalhaven, the project plans are already in a further stage. The projects mainly serve as a 'show case'; this is the direction for energy carrier of road transport that the Port of Rotterdam is going to take. The Port aims to give a kick-start to the market and hopes to solve partly the chicken-egg problem, after, the market the aim is that the market should provide the charging facilities. The long term proposal of the Port is that logistic companies should provide charging facilities also at their own premises, where they load and unload freight. The charging at own depots is expected to be cheaper for logistic companies and also counters the space scarcity in the port area. In addition, the projects are in line with the strategy to remain accessible and to decarbonize towards 2050. The Port has already provided financial support and has connected several stakeholders (Voskamp & Dodemont, 2022).

The roll-out strategy briefly reflects on hydrogen trucks, which is considered relevant for long-distance transport. Hydrogen trucks could also be relevant since several requests for hydrogen fueling stations are coming from external parties to the Port, while these requests are less for electric charging facilites. However, it states that on short term there are sufficient opportunities for fueling hydrogen, which is taken care of by the market. Therefore, the Port of Rotterdam requires currently less attention to accelerate the hydrogen fueling facilities (Voskamp & Dodemont, 2022).

Other concerns besides the space scarcity, are limited grid capacity and potential grid congestion. For the Bodaanweg project, the grid had to be upgraded by Stedin to a grid connection of 5MVA, also a transformer, low voltage installations and charging equipment had to be bought and installed. Bodaanweg starts with 2 fast charging spots during the day and 4 or 6 slow chargers for overnight charging. The number of fast charging stations can be scaled up in the future to approx. 8 – 10 fast chargers. Project Bodaanweg could also provide insights how the market will respond to the charging facilitation (Port of Rotterdam, 2022a).

B. Assumptions for the SCBA-case study

In this appendix B the core assumptions for the case study are further defined. It provides insights on the considered fleet of the corridor, the distances and the amount of trips driven. The discount rate is also defined.

Fleet characteristics

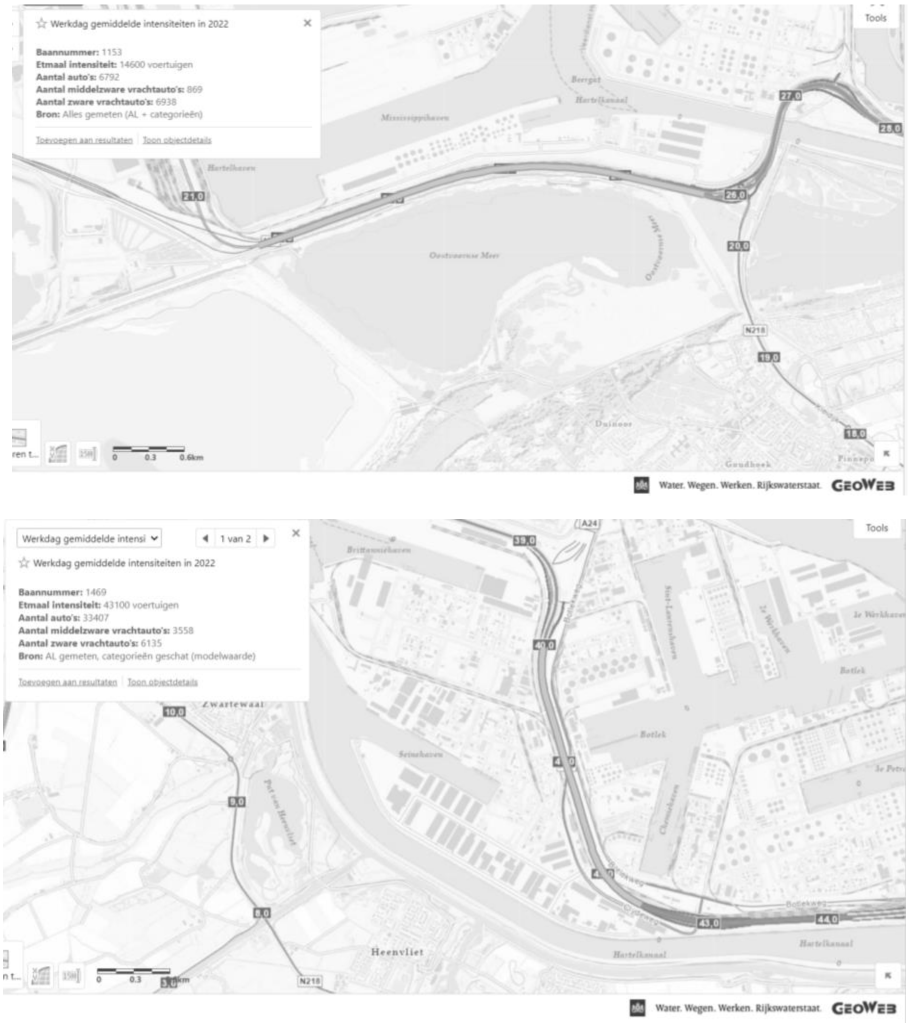
In the case study only the costs and the benefits of the Rotterdam – Duisburg corridor are assessed. The corridor consists of A15, N322, A73/E31, the A57, to the Am Brink in Duisburg and the A40 towards Duisburg-Hochfeld/Duisburg-Zentrum (Google Maps, n.d.). For the corridor only the highway is regarded. The inner city and provincial roads are left out of scope. A distance of 240 km is taken, that comprises the corridor (Klein et al., 2020).

Since the corridor solely comprises 240 km, the corridor is perceived as a short-haul transport. Since < 400 km truck-distance are classified as short-distances according to Gray et al. (2021). This classification is relevant since for battery electric vehicles a smaller battery would be established in the vehicle for short-haul transportation. A shorter range has a less negative impact on the payload (Nykvist et al., 2021). The smaller battery requires less space, thus more space would be left for the transport of goods. The payload would thus not decrease. In the case study the payload of all considered types of energy carriers is assumed to remain constant in the heavy-duty vehicles.

The focus is on heavy-duty vehicles (HDVs) in the research as earlier mentioned, since the type of trucks that mainly drive in the hinterland of the port of Rotterdam to transport road freight are HDVs, this is based on the data of INWEVA (GeoWeb 5.5, n.d.). In Tol et al (2022) three types of heavy-duty trucks are distinguished, which are rigid truck, articulated truck, tractor-trailer, but in this research no distinction is made between the HDVs. In the report of Fabius et al. (2020) the weight class for HDVs is defined as above 18 tons (18.000 kg). However, in the report of Cunanan et al. (2021) a vehicle is classified as HDV if the gross vehicle weight is greater than 26,000 lbs, which is 11.800 kg. Therefore, in the data-collection a reflection is made on the weight of the HDVs if numbers are obtained from a report. For all types of energy carriers-HDVs a lifespan of 8 years is assumed, similar to the depreciation period defined in Tol et al. (2023).

Due to the specific characteristics of the markets that the modalities serve (Port of Rotterdam, n.d.-a), it is assumed that no modal shifts are made between road to inland shipping or rail freight in the case study.

The amount of heavy-duty trucks that drive on the corridor and is considered in the case study is based on the data of INWEVA. The average daily number of heavy-trucks is defined per corridor and summed for both directions. Two points are regarded on the A15, these show 6938 heavy-trucks per average workday both directions included at the N15 and 6135 at near the Botlek, these observations are shown in figure 33. An average of the two points is assumed for the beginning of the A15 corridor. As vehicles go off and onto the road, this amount of heavy-duty trucks will be included in the SCBA for the corridor between Rotterdam and Duisburg. The amount of heavy-duty vehicles will remain constant between the different strategies.



☆ Werkdag gemiddelde intensiteiten in 2022

Baannummer: 1153
Etmaal intensiteit: 14600 voertuigen
Aantal auto's: 6792
Aantal middelzware vrachtauto's: 869
Aantal zware vrachtauto's: 6938
Bron: Alles gemeten (AL + categorieën)

Toevoegen aan resultaten | Toon objectdetails

☆ Werkdag gemiddelde intensiteiten in 2022

Baannummer: 1469
Etmaal intensiteit: 43100 voertuigen
Aantal auto's: 33407
Aantal middelzware vrachtauto's: 3558
Aantal zware vrachtauto's: 6135
Bron: AL gemeten, categorieën geschat (modelwaarde)

Toevoegen aan resultaten | Toon objectdetails

Figure 33. Observations of road freight on the A15

Note. Taken from GeoWeb 5.5 (n.d.). https://maps.rijkswaterstaat.nl/gwproj55/index.html?viewer=Inweva.Webviewer

The fleet growth factor for the entire fleet, thus of all energy carriers considered, is assumed to be 1,5 % per year. This is based on the features of CBS. According to the features of CBS in 2023 the amount of rigid trucks decreased by 0,1 % compared to 2022. For tractor-trailers a growth of 3,9 %, from 2023 compared to 2022 was observed, based on the features of CBS. From 2021 to 2022 an increase of 0,2 % was observed of rigid trucks and an increase of 3,1 % of tractor-trailers (Centraal Bureau voor de Statistiek., n.d.).

Trips and distance*s*

The trips that the fleet drives each year are defined based on the Dutch legislation about mandatory resting. The Dutch Ministry of Infrastructure and Water Management (2022c) made several rules for the resting time of drivers. The maximum uninterrupted driving time must not exceed 4.5 hours, after driving 4.5 hours a break of 45 minutes must be taken. The 4.5 hours may be divided in more parts, but breaks must at least take 15 minutes and one break must take 45 minutes. A maximum of 90 hours is a driver allowed to drive per 2 weeks. This applies to weeks 1 and 2, but also to weeks 2 and 3, and so on. In one week a driver may drive 56 hours, but this is not allowed for two weeks. Loading and unloading also counts as working time

(Ministerie van Infrastructuur en Waterstaat, 2022c). Since for two weeks a maximum of 90 hours is allowed, an average 6,43 hours driving a day is assumed, besides this driving time there would be sufficient time for recharging/refueling or loading/unloading. A maximum speed of 80 kilometers per hour applies to freight traffic according to the Ministry of General Affairs (2023) and it is assumed that the trucks drive 260 days each year, similar to the research of Tol et al. (2023). Based on these figures the amount of trips per year and the total driven distance each year are calculated. It is therefore indirectly assumed that there is one driver per truck, the occupancy rate by drivers can therefore not exceed the amount of trucks.

Three different distances for the trips are assumed on the corridor: 50 km, 150 km and 240 km. This is shown in table 11. Since the Port of Rotterdam (n.d.-b) states that 40% of the road transport remains within the region, 50% is for the Dutch market and 10% goes to foreign countries. The distances are assumed to remain constant over the years.

Table 11. Distances assumed driven on the corridor Rotterdam – Duisburg

	Region	Dutch Market	Foreign country
Share of the fleet [%]	40	50	10
Distance assumed for X Fleet percentage [km]	50	150	240

The total distance driven by the fleet is based on the assumed fleet size, the shares of the fleet that drive a corresponding assumed distance, the average trips that are made each day and the limited working days each year. The formulas that are used for the fleet related characteristics are shown in figure 34.The share of the fleet that drives a type of energy carrier is also defined based on the defined formula in figure 34. For the zero-alternative and the strategies the data for the share of S differs.

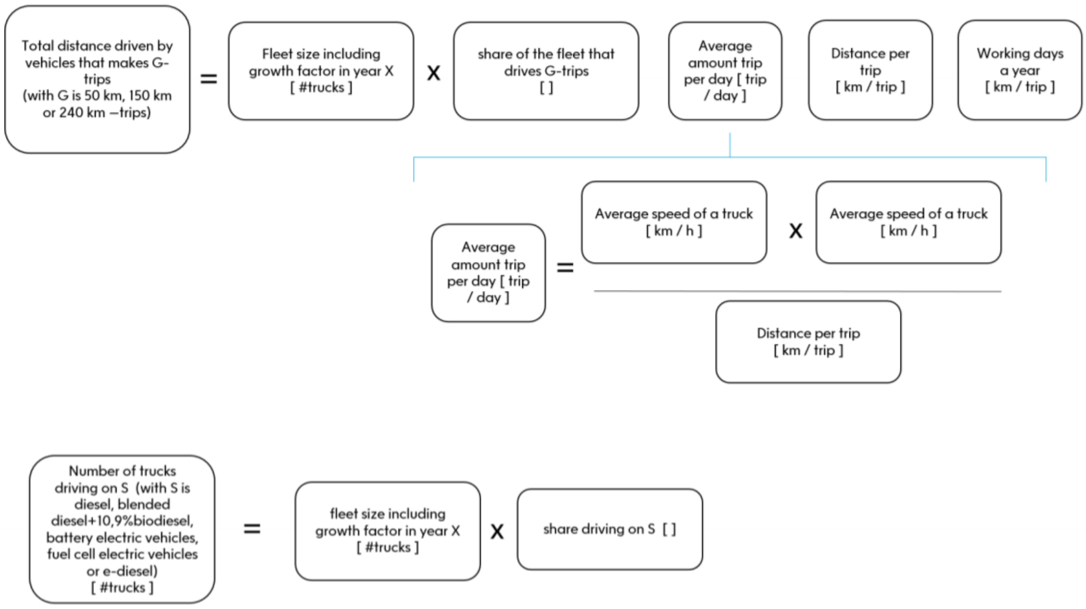


Figure 34. Fleet characteristics related formulas used

Discount rate

In the social-cost and benefit analysis the standard discount rate of 2.25 % is applied. This level of discount rate is chosen because the 2.25 % is applied to all types of policy changes and all types of costs and benefits in a SCBA (Ministerie van Financiën, 2020). Influences on the discount rate through inflation caused for example by the Russo-Ukrainian War have not been taken into consideration in this study.

C. Different energy carriers and technologies compared

Conventional fuels

The conventional fuels, which are diesel, petrol and LPG (Tol et al., 2023), are most common used nowadays. By solely using the conventional fuels the climate targets will not be reached (Cunanan et al., 2021). Diesel is used as a reference point in the case study similar to the study of Tol et al. (2023), since diesel is currently most used by heavy-duty vehicles according to Cunanan et al (2021). Diesel can be used in an internal combustion engine. Diesel has advantages compared to other energy carriers and therefore on short term it is expected that diesel remains an important energy carrier even though the emissions that the energy carrier causes are high. Diesel has the advantage of having a relatively long range of 975 – 1950 miles for a tank of 150 – 300 gallon, without any stops to refuel and refueling time is also relatively short taking 6 – 12 minutes. The exact range depends on topology and traffic. The purchase for a heavy-duty truck with internal combustion engine and the usage costs of diesel currently still has the lower costs compared to other energy carriers. The infrastructure also already exist (Cunanan et al., 2021). In terms of range, refueling/recharging time and the already existing infrastructure, battery electric trucks currently remain less competitive (Cunanan et al., 2021).

Electricity

Electricity that is used in battery electric vehicles (BEVs) is considered as a promising decarbonization option for heavy-road freight transport in order to replace conventional fuels. This is mainly due to the promising results on the energy efficiency, the costs and the potential emission reductions of battery electric vehicles (Tol et al., 2023).

BEVs are most energy efficient due to the few conversion processes and high level of efficiency of the drivetrain, which results in a lower energy demand compared to other energy carriers. The well-to-wheel energy consumption of long haul articulated trucks in the Netherlands is 4 MJ per km for a BEV, while for a fuel cell electric vehicles (FCEVs) this is 17 MJ per km and for e-diesel this is 24 MJ per km. This results in an lower energy demand for BEVS, compared to the energy demand for FCEVs and for e-diesel.

In addition, the production process for electricity that is used in an electric motor requires less energy compared to the production of hydrogen (used in a fuel cell) and the production of e-diesel (used in an internal combustion engine). This is mainly due less conversion processes, for which more energy is required. This is shown in figure 35.

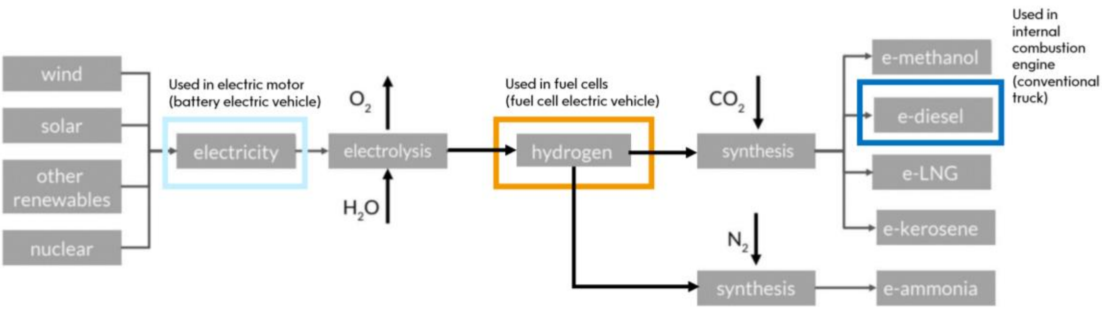


Figure 35. Production process energy carriers

Note I. Taken from “The potential of e-fuels for heavy-duty road transport in the Netherlands,” by Tol, D., Verbeek, M.M.J.F., Gaggar, S., Hulsbosch-Dam, C.E.C., Vredeveldt, A.W., van Zyl, P.S., van Ark E.J., Paschinger, P., Smokers, R.T.M. (2023). TNO, p.24, Available at Smartport.nl
Note II. The colored blue and yellow blocks are added based the statements of Tol et al. (2023).

Considering the total costs of ownership (TCO), the TCO of BEVs is expected to be lower than the TCO FCEVs and the TCO of trucks that use e-fuels (Tol et al., 2023). The TCO is a term used for the total cost during possession. It comprises all costs associated with purchasing, using and owning a vehicle over a period of time (Fabius et al., 2020). This is the case from 2020 to 2050. Therefore the BEV would be a more competitive way for transportation (Tol et al., 2023). In addition, battery electric vehicles have 20 – 30% lower maintenance costs compared to conventional diesel-powered vehicles, partly due to the less mechanical moving parts, because there is no conventional engine (Cunanan et al., 2021). Parviziomran et al. (2023) also makes a distinction on the distances for the TCO. In case of a shorter distance, the BEVs is earlier more competitive considering the TCO.

Regarding the emissions, the tailpipe emission of battery electric trucks are zero taking a tank-to-wheel scope. This includes the emissions from refueling and the tailpipe emissions. From a well-to-pump scope, which includes the emissions released during the production and the transport to the final consumer, the BEVs would only release zero-emissions if renewables were used to generate the energy (Cunanan et al., 2021).

However, the implementation of BEVs also faces some challenges regarding the impact on the operational activities of the service provider due to the limited range that the battery currently offers. BEVs have the smallest range in comparison to hydrogen, e-fuels and conventional fuels. The current range of a BEV is around 220 km on a battery capacity of 350 kWh and it is expected to go up to 750 km on a battery capacity of 950 kWh (Tol et al., 2023). Large batteries are required for a larger range (Plötz et al., 2023). The concern is mainly the weight of the battery and the capacity required within the freight vehicle, which could result in a smaller capacity for the loaded freight (Cunanan, et al., 2021). The recharging time also remains longer than the refueling time of the other energy carriers. The recharging time could be reduced, but fast charging has the concern of a shorter overall battery life (Cunanan et al., 2021). However, depending on the logistic planning, Tol et al. (2023) states that the expected ranges of BEVs are sufficient for 85 – 95% of all tractor trailers, also partly because 65% of the tractor trailers drive 95% of the days less than 580 km (Tol et al., 2023).

Another barrier is the lack of availability of the recharging infrastructure. However, in the regulation of Alternative Fuel Infrastructure Regulation (AFIR), new conditions for recharging facilities on the main European roads are proposed. The capacity of the electricity grid also needs to be able to handle the demand at the recharging places at the right time. This could be uncertain due to the increasing demand for electricity in other sectors in Europe. Another concern is the availability of materials that are required for the production of batteries (Tol et al., 2023).

Considering all the barriers, it is unlikely that BEVs will replace all vehicles in the fleet according to Tol et al (2023).

The plug-in hybrid trucks, which could be seen as an intermediate variant of the BEV and are not able to achieve the climate targets (Ainalis et al., 2020). Therefore, the plug-in hybrid trucks are left out of scope in this study.

Electrification performance amplifiers

An Electric Road System (ERS) can enhance the performance of electric vehicles by more direct electricity use due to a limited number of conversion processes. ERS is an technology that allows vehicles to charge during their movement (Bateman et al., 2018). According to Pastowski (2017) this could make a high contributions to decarbonization compared to other options mainly based on the energy efficiency-criteria. According the Bateman et al. (2018), ERS could overcome the difficulties of high purchase costs, limited battery range and a lack of charging convenience for heavy-duty vehicles.

There are three options for ERS distinguished; the conductive overhead line, conductive rail and inductive charging (wireless) (Lechtenböhmer et al., 2018; Bateman et al., 2018; Ainalis et al., 2020). The three options can reach the same energy efficiency (Lechtenböhmer et al., 2018). However, due to the highest level of technological readiness, the lowest infrastructure investment costs, the less safety concerns and less maintenance activity difficulties (Ainalis et al., 2020; Bateman et al., 2018; Lechtenböhmer et al., 2018), only the catenary electric road system is further considered in study.

The Catenary Electric Road System (CERS) comprises overhead catenary wires, power supply and compatible electric vehicles with a deployable pantograph system, battery and electric drive. The current collectors should be aligned with the overhead wire-system, thereby the electric vehicles can connect and disconnect from the CERS at all speed (Pastowski, 2017).

However, the CERS concept also knows several challenges, which should probably been taken care of on European scale, since it would cause more difficulties to implement the CERS solely in the Netherlands or Germany. For the CERS investments in overhead wires and electric vehicles with deployable pantograph systems are required. It is questionable how this may be financed, considering the implementation of the overhead wire infrastructure require a long build-up period, it will initially have a low spatial coverage on the highways and a small turnover from its use. It is also questionable whether logistics service providers are willing to make investments in the aligned vehicles, since these vehicles probably will be more expensive (Pastowski, 2017).

Hydrogen

Hydrogen fuel cell vehicles (FCEV) and hydrogen internal combustion engine vehicles (HICEV) could both be an option to decarbonize road freight. An advantage of the hydrogen trucks compared to the BEVs is that the range is expected to exceed the range of BEVs. The range of e-fuels is expected to be larger than the range of hydrogen trucks. The range of HICEV currently is 420 km and is expected to grow to 850 km, for FCEV the current range is 530 and the expected is 1100 km (Tol et al., 2023). The refueling time of hydrogen, with 16.67 minutes for fuel cells, is also shorter than the recharging time for BEVs (Cunanan et al., 2021), due to more flexibility the way of transportation could therefore be more competitive. The TCO, of hydrogen trucks, both FCEV and HICEV, remains higher than the TCO of battery electric vehicles until 2050, but is expected to be equal to the TCO of e-fuels according to Tol et al., (2023). Plötz (2022) mentions that the tariffs of hydrogen are uncertain in the future. For ports the tariffs also might be different, because the cost of H_2 might be lower. These lower costs of H_2 are due to the potential surplus of hydrogen through the proximity green electricity of off-shore wind in a port (Tol et al, 2022). The tariffs are also reflected on in the TCO. In case of a lower tariff, the TCO is also lower.

Considering emissions, hydrogen fuel cell trucks are comparable to battery electric vehicles. Since hydrogen fuel cell trucks emit no harmful tailpipe emissions and hydrogen with an internal combustion engine do emit PM and NO_x (Tol et al., 2023), in this study trucks with a fuel cell are therefore taken into further consideration. From a wheel-to-tank perspective, CO_2 emissions are low if green or blue hydrogen is used (Ainalis et al., 2020). Tol et al. (2023) scores the applicability and flexibility of green hydrogen in fuel cell vehicles positive in 2030, therefore it is also assumed that green hydrogen is available from 2030 onwards. Sens et al. (2022) also assumes the availability of green hydrogen from 2030 onwards. Plötz (2022) states the expected amount of green hydrogen in 2030 is limited.

Regarding safety aspects, hydrogen has a high level of risk for flammability and a high risk for explosion. This is for both forms of hydrogen in a compressed gaseous form and in a cryogenic liquid form as well. The main difference is the storage handling for gaseous hydrogen tanks are required for a storage pressure of 350 – 700 bar and for liquid hydrogen a storage cryogenic temperature of – 252 C is required (Tol et al., 2023).

A barrier for the usage of hydrogen for trucks is the lack of provisioning of refueling infrastructure (Cunanan et al., 2021). In addition, it is difficult to get the hydrogen at acceptable costs to the refueling stations. This could either be done by pipeline connections, transportation by tube trailers or local production. Pipeline connections could probably only be provided if there is also a necessity for other applications. If this application would be the case, also costly purification of the hydrogen would be required for the use in fuel cells. This is not necessary for the use in combustion engines. Regarding the transportation by tube trailers, costs would be high because of the many trips required. Since only a small amount can be transported per trip. For the local production, also larger storage provisioning needs to be made and the electricity grid needs to be reinforced. Transportation by tube trailers is expected to be the main way of getting hydrogen at the refueling station until 2030, it is assumed that those tube trailers used for transportation are electric (Tol et al., 2023).

Hydrogen trucks score lower overall on the criteria compared to BEVs considering the TCO, the safety aspects and the unavailable infrastructure. If hydrogen would be distributed by pipeline or would be produced locally at gas station, the energy loss could also be lower. This would also result in a lower value of the TCO. However, the research of Tol et al. (2023) concludes that there is a relatively high risk to invest in the infrastructure for hydrogen because of the uncertain demand, which is probably limited to the long-distance transport (Tol et al., 2023).

E-fuels

Tol et al. (2023) states that e-fuels are a potential option to decarbonize heavy-duty transportation for mainly longer distances. E-fuels can be produced with a combination of hydrogen and CO_2. The e-fuels are produced more sustainable if the hydrogen is made by using solar or wind energy, and if the CO_2 is captured either direct from the atmosphere or from flue gases. There are different types of e-fuels which are e-diesel, e-methanol, e-LNG and e-DME, these e-fuels can be used in a combustion engine. Tol et al. (2023) states that e-diesel and e-methanol of all e-fuels are the most promising options to decarbonize road freight. E-diesel delivers the user the most flexibility due to the largest range and since e-diesel has a higher level of commercial readiness for infrastructure and vehicle compared to e-methanol according to Tol et al (2023), therefore is e-diesel further considered in this research project.

E-fuels have several major advantages compared to the other decarbonization options. E-diesel scores the highest on level of safety and leads to most flexibility due a high range and due to the short refueling time. The range of e-fuels outperforms BEVs. The TCO expected for 2030 of the e-fuels are expected to be equal to the TCO of hydrogen trucks (Tol et al., 2023). Moreover, for the use of e-diesel the current fueling infrastructure and engine technology of the vehicles do not have to be adapted to a large extent (Tol et al., 2023; Prussi et al., 2022). Another advantage of the e-fuels is that it enables chemical storage for renewable electricity, in case a peak would be produced that cannot be handled by the grid. Therefore, the e-fuel could also contribute to balancing the grid. This implies that the distribution grid needs less improvements, which probably would be necessary if BEVs would have a high uptake (Prussi et al., 2022).

However, the usage of e-fuels also knows several challenges. E-fuels are commercial ready after 2040, since the production of e-fuels is expected to be viable in 2040 which might be too late to reach the climate goals. Biofuels could serve as a transition fuel until 2040, because these could also use the existing infrastructure to a large extent. The production would also require lots of electricity, for this generation a larger amount of energy and corresponding space is also necessary due to more conversion processes. More renewable electricity is required compared to more direct application in BEVs for example. This results in an overall lower efficiency of the energy chain (Tol et al., 2023. Moreover, Bosteels, et al. (2022) states that e-diesel have the potential to become carbon neutral from a well-to-wheel perspective. Van Kranenburg et al. (2020) also states that e-diesel could be zero-emission from a well-to-wheel perspective. A scale-up of the production of e-fuels is mentioned from 2035 onwards, but when it becomes zero-emission remains unaddressed. The production could be could take place in the Port of Rotterdam (Van Kranenburg et al., 2020). If the production would take place in the port area, it could be argued that the tariffs for e-diesel would be lower in the port area. This is mainly due to the reduced costs of e-fuels, since not transportation would be required.

However, the production costs of the e-fuels are very expensive, resulting in high fuel costs (Ainalis, 2020). Furthermore, the use of e-fuels would still cause tailpipe emissions as CO_2, NO_x and PM. Since it combusts a carbon-based fuel, it first extracts CO_2 from the atmosphere the CO_2 net emissions can be considered zero (Tol et al., 2023). The current EU legislative framework is a TTW approach for the level of CO_2 emissions allowed, this would not allow to use the e-fuels. However, if a WTW perspective is taken 94% of CO_2 emissions would be reduced by using e-diesel for heavy-duty transportation (Prussi et al., 2022).

Tol et al. (2023) concludes that a relatively small market share of e-fuels for heavy-duty transportation is excepted and even the small market remains uncertain due to the potential of electric trucks and the competition with hydrogen. However, the investments risks are relatively low compared to hydrogen, since the existing infrastructure can be used to a large extent. The application of e-fuels in other sectors like aviation and shipping are expected, which could increase the demand of e-fuels (Tol et al., 2023). In case the demand increases and production is scaled, economies of scale could occur (Prussi et al., 2022).

Biofuels

According to Tol et al. (2023) biofuels in combustion engine could be used as an intermediate option between now and 2040 to decarbonize heavy-duty transport. Biodiesel, bioethanol and methanol are examples of biofuels, from which biodiesel and bioethanol are the most commonly used biofuels (Panoutsou, 2021; Ajanovic & Haas, 2021). In the 'operational greenhouse gas scenario' -study of Frank et al. (2022), in which the carbon emissions were internalized and the financial viability was regarded, bio-based diesel had the most promising NPV and the second lowest operational carbon impact compared to battery electric vehicles. The study of Frank et al. (2022) did not include a social cost-benefit analysis.

Biofuels could be blended with fossil fuels or e-fuels. A major advantage of the (blended) biofuels are that the existing infrastructure and the engines used for fossil fuels do not need to be altered for a large extent (Tol et al., 2023). In addition, the costs are competitive with diesel (Ainalis et al., 2020). The potential of using biofuels depends on the availability, which is partly determined by the direction that the entire mobility sector is taken regarding the energy carrier options. The production of biofuels could be driven by the maritime and aviation sector, because these sectors will probably be either using biofuels or e-fuels due to the energy density of the carriers (Tol et al., 2023). Panoutsou et al. (2021) confirms that advanced biofuels can offer a solution to decarbonize heavy-duty vehicles in the short to medium term. However, it also mentions that raw materials for fossil fuels have a higher energy efficiency level, without considering the external costs biofuels are less competitive. Ajanovic and Haas (2021) conclude that for now for heavy-good vehicles the competition by biofuels to electric vehicles is very low.

However, biofuels have tailpipe emissions and are limited available to deploy widely (Ainalis et al., 2020). Due to these the set targets towards 2050 might not be achieved by solely relying on this fuel. In addition, Tol et al. (2023) expects that methanol will exceed the emission limitations of NO_x and PM as stated in Euro VI.

Natural gas

LNG and CNG can be distinguished as natural gas. Both can be used in a conventional vehicle with an internal combustion engine (Tol et al., 2023). The CO_2 reductions by using LNG as energy carrier would be limited according to Patowski et al. (2017). In addition, LNG is expected to exceed the European emission limits of NO_x and PM for heavy-duty vehicles as stated in Euro VI. Regarding the safety aspects of flammability and health concerns, LNG also has a bigger hazard compared to conventional diesel (Tol et al., 2023). The advantage is that LNG would have a high level of technological readiness compared to hydrogen and ammonia according to Patowski et al. (2017), but due to the perceived limitations it is not taken in further consideration.

According to Sen et al. (2017) CNG-trucks are outperformed by battery electric trucks. In the analysis different alternative fuel technologies are considered for heavy-duty trucks, which are biodiesel and hybrid, battery-electric trucks. In addition, the study concludes that CNG trucks will give no improvements in life-cycle environmental impacts and life-cycle costs (Sen et al., 2017). CNG has also a high risk of flammability. CNG can be stored at an high pressure around 250 bar, but therefore more advanced storage and handling techniques are required. Regarding all considered risks in Tol et al. (2023), CNG is perceived as more hazardous than conventional fuels and will therefore not be taken into further consideration during the research project.

Ammonia

According to Dimitriou and Javaid (2020) ammonia (NH_3) can be seen as an option to decarbonize heavy-duty transportation. Ammonia can be combusted and thus be used in a conventional vehicle with an internal combustion engine. It can be combusted in a ‘dual-fuel mode’ with diesel or another lower autoignition temperature fuel. Only small modifications are needed to a conventional internal combustion engine to operate ammonia. The use of ammonia would result in significant carbon-based emissions reduction. However, the combustion of dual-fuel ammonia would cause NO_x emissions, as a result of the fuel-bound nitrogen (Dimitriou and Javaid, 2020).

Patowski, et al. (2017) mentions ammonia could have a risk for toxicity. Tol et al. (2023) confirms that ammonia is toxic and adds that is also corrosive. Therefore, there is more effort needed to meet the additional requirements for storage and handling in order to reduce the risk for human health. Ammonia could be hazardous to inhale (Dimitriou and Javaid, 2020). The risk of flammability and explosion of ammonia are relatively low compared to conventional fuels and hydrogen (Tol et al., 2023). Due to the risk of toxicity and the caused NO_x emissions after combustion ammonia is not taken into further consideration during the research project.

D. Data for the zero-alternative and proposed strategies

Vehicle related data

Table 12. Vehicle cost projections for 2020, 2030 and 2040

Vehicle cost projections in k€	2020	2030	2040	Line of reasoning	Source
Diesel trucks	143	158	169	The costs of a trailer vehicle are included in these numbers. The numbers of the central or mid scenario are considered. Tax, a reflection of demand and supply and potential profit margins are not included in these numbers (Tol et al., 2023).	All vehicle cost projections are stated in Tol et al. (2023).
Battery electric trucks (400 kWh)	343	187	164		
Battery electric trucks (750 kWh)	487	217	183		
Hydrogen fuel cell trucks	494	274	226		
E-diesel trucks	143	158	169		

Table 13. Maintenance costs per vehicle

Maintenance costs per vehicle	Maintenance Costs	Assumption	Source
Diesel trucks	7000 euro/year/vehicle	It is assumed that the maintenance costs for the vehicles remains constant over the years. Since fossil diesel also uses an internal combustion engine just like e-diesel, therefore the same amount of maintenance costs are assumed as for an e-diesel vehicle.	All maintenance costs are stated in Tol et al. (2023).
Battery electric vehicles	3500 euro/year/vehicle		
Fuel cell electric hydrogen vehicles	5250 euro/year/vehicle		
E-diesel trucks	7000 euro/year/vehicle		

Table 14. Current HDV-fleet shares in the Netherlands

	Amount of trucks in NL	Percentage of fleet around 2020	Line of reasoning	Source
Diesel + biodiesel blended mix	-	100 % – 0.16 % – 0.01 %	The European Union agreed that in 2020, at least 10% of the fuel in transport should consist of alternative sustainable fuels, such as biofuels. In this study it is therefore assumed that at least > 10 % of the conventional fuel comprises biofuels. In this study it is also assumed that the heavy-duty fleet comprises 100 % and that the diesel blended biodiesel mix comprises 100 % - BEVs – FCEVs.	Ministerie van Economische Zaken en Klimaat, 2019
Battery electric vehicle > 3.5 ton	254	0.16%	It is assumed that all trucks above > 3.5 ton are HDVs, since this is the highest weight class defined in the source and no other source is identified about the same relevant data.	Netherlands Enterprise Agency, 2022
Fuel cell electric vehicle > 3.5 ton	24	0.01%		
Plug-in hybrid electric vehicle	33	0.02%		

			Since diesel plug-in Hybrid (Euro VI) trucks have unsustainable emission factors according to Klein et al., (2020), it is assumed that through developments of either battery electric vehicles or other forms of ze-road transport will be more dominant. It is assumed that the hybrid-vehicles will not have a bigger share in the heavy-duty vehicle segment and it is therefore further left out of scope in this study.	

Table 15. Predictions for HDV-fleet shares in the Netherlands

	2030	2040	2050	Line of reasoning	Source
ZE-emission predicted share	5 %	13.6 %	40.9 %	Fabius et al. (2020) states that in 2030 for the heavy-duty segment between 0-5% of all vehicles drives on ZE-vehicles, which would be BEVs or FCEVs. Since the TCO in 2030 is more attractive of BEV than of FCEV the same ratio of 2020 is used 16 BEV : 1 FCEV. In 2040, 20.000 ZE-vehicles, which would be BEVs or FCEVs, in the heavy-duty segment are read by a graph of Fabius et al. (2020). This is 18,9% of the total fleet of 110.000 of HDVs. The same rate as in 2030 is assumed for 2040 of BEV / FCEV = 16 / 1 , since the TCO_BEV < TCO_FCEV. In 2050, 47.000 ZE-vehicles, which would be BEV or FCEV, in the heavy-duty segment are read by a graph of Fabius et al. (2020). This is 42,7% of the total fleet of 110.000 of HDVs. The same rate as in 2030 is assumed for 2050 of BEV / FCEV = 16 / 1 . It is important to emphasize that the percentages are based on assumptions. Noordijk et al. (2020) expects 42 % of the fleet of inter (national) trucks to be electric in 2035. However, since Fabius et al., (2020) is perceived as more objective, this source is used for the case study.	Fabius et al., 2020 Noordijk et al., 2020
Amount of ZE-vehicles predicted	5,500	15,000	45,000		
Share BEV - HDVs	4.7 %	12.8%	38.5 %		
Share FCEV - HDVs	0.3 %	0.8 %	2.4 %		
Amount BEV predicted	5,177	14,118	42,353		
Amount FCEV predicted	324	882	2647		
In the Excel model linearity is assumed for the development of the fleet in total, but also for the shares of trucks that drive on blended diesel + biodiesel, BEVs, FCEVs, trucks that drive on e-diesel. For the linearity-function the share in 2020 is taken and the share in 2050 is considered. The shares in between depend on the year between 2023 – 2050.					

Station related data

Table 16. Amount of recharging and refuelling stations

	Current amount of recharging / refueling station in 2023	Proposed by Alternative Fuel Infrastructure Directive (AFIR)	New amount of recharging/refueling stations + one station in the port of Rotterdam and one station in Duisburg	Source
Diesel tank stations	15 stations are identified on Google Maps. The following tankstations are identified where diesel can be tanked: Tango Europoort (A15, Europaweg); Shell (Vondelingenweg A15); Shell (Rijksweg 2 ZZ, A15); BP (Ridderkerk A15); ESSO (Rijksweg A15 both directions); Tango Rumpt (A15); Shell (Rijksweg NZ); Shell (Rijksweg E1 NZ); Shell (Rijksweg A15 ZZ, 4156); BP (Maas en Waalweg N322); Total (Rijksweg A73); Shell (Rijksweg A73); Aral (A57); Shell (A57).	The existing infrastructure can be used, thus it is assumed that no further costs need to be made to built new tankstations.	0	Cunanan, 2021 GoogleMaps, 2023
Recharging stations	0 recharging stations are identified on Google Maps. Currently, a few stations for recharging of battery electric vehicles directly along the highway of the corridor Rotterdam – Duisburg can be identified. On Portland	For rechargers 4 places of 350 kWh per 60 km is proposed for 2025 and 10 places of 350 kWh per 60 km in 2030 along the A15 are required.	6 + 2	Blauuw, personal communication, 2023 Tol et al., 2022 Google Maps, 2023

	A15, Ridderkerk A15, Alblasserdam A15; Steenenhoek A15; Lokkant A73, there are FastNed stations. These recharging stations are owned by the company FastNed. These stations were initially designed for passenger vehicles and light commercial vehicles (up to 7.5 tons). Vehicles heavier than 7.5 tons are currently not welcome at the stations, mentions FastNed in the mail contact. Mainly due to safety reasons related to passenger vehicles. In addition, at the older (arch) stations it is not possible to get to the station with a high vehicle (max. 2.75 m). FastNed is currently investigating which locations already might be suitable for > 7.5-tonne vehicles, and which locations require adjustments and what exactly needs to be adjusted. E.ON Charging Station, A57. It remains unknown if recharging for heavy-duty vehicles is possible here.	This leads for the corridor of 240 km to a minimum of 6 stations.		

Fuel cell electric hydrogen vehicles	0 hydrogen refueling stations Two hydrogen refueling station in operation are identified along the corridor in Rhoon, the A15 and the Total in Duisburg. However, it remains unknown if these are already suitable for heavy-duty freight. Therefore, it is assumed that new stations need to be build.	For hydrogen stations along the highway 1 station with 2 ton/day capacity per 150 km in 2030 along the A15 are required. This leads to 3.6 hydrogen stations in total. Thus, rounded 4 new stations to comply with the AFIR.	4 + 2	Archief Locaties - H2Platform, n.d. Google Maps, n.d. Tol et al. 2022
E-diesel trucks	15 e-diesel refueling stations Since the same infrastructure as diesel can be used for e-diesel.	To a large extent biofuels and e-diesel can use the existing infrastructure and the conventional internal combustion engine according to Tol et al. (2023). Therefore, no further investments are assumed for building the refueling stations, only maintenance costs are assumed.	0	Tol et al. 2023

Table 17. Costs for recharging and refuelling stations

Costs for recharging and refueling stations	Costs	Line of reasoning/assumptions	Source
Diesel refueling station	-	The existing infrastructure can be used, thus it is assumed that no further costs need to be made to built new tankstations.	Cunanan, 2021
Recharging station costs at truck plaza	2022 → 1,030,600 euro	These costs comprises the following aspects: grid connection Stedin (5 MVA), transformer including work, low-voltage installations + project costs Truck parking and the charging equipment. Only the related civil works are later determined. The Port of Rotterdam will take financial responsibility for the grid connection of 500 – 550 k€. In this study it is assumed that 50 % is covered by either the government or the Port Authority. This is for 2 fast charging spots during the day and 4 or 6 slow chargers for overnight charging.	Port of Rotterdam, 2022a
Hydrogen refueling station (For a capacity of 2 ton/station)	2020 → 5,000,000 euro 2030 → 3,900,000 euro 2040 → 3,500,000 euro	Further specifications on the costs are unidentified in the report of Tol et al. (2023) and the report to which is referered Ricardo (2021) also remains unidentified. However, the number of 5.000.000 euro is approxamitely confirmed in the rapoort of Ainalis et al. (2022), in which 1000 refuelling stations supplying green hydrogen, are constructed in 5 years and for which the total capital expenditure is estimated 5 billion pound.	Tol et al. 2023 Ainalis et al. 2022
E-diesel refueling stations	-	To a large extent biofuels and e-diesel can use the existing infrastructure and the conventional internal combustion engine. Therefore, no further investments are assumed for building the refueling stations, only maintenance costs are assumed.	Cunanan et al., 2021

Catenary Electric Road System related data

Table 18. Costs for the CERS

Costs for the catenary electric road system	2025	2030	2035	2040	Line of reasoning/assumption	Source
Pantograph costs	17,500 £ /vehicle	15,000 £ /vehicle	12,500 £ /vehicle	10,000 £ /vehicle	For the years of 2030 – 2040 the numbers are directly obtained. The number of 2025 is defined based on a linear curve.	All numbers are obtained from Ainalis, Thorne, & Cebon, 2020
CERS system costs	80M£/40 lane-km	5625 M£/3261 lane-km	5746 M£/4759 lane-km	7918 M£/7062 lane-km	The numbers are directly obtained and include the following: the catenary costs, the transformers and roadside cabling, the grid connection, safety barriers, land purchase, estimated non-capital costs and indirect costs.	
Corresponding construction period for the CERS system	1 year	2.7 year	2.6 year	2.7 year	The numbers are directly obtained.	
Maintenance costs for CERS	2 % of capital costs / year	2 % of capital costs / year	2 % of capital costs / year	2 % of capital costs / year	The percentage was defined for the annual infrastructure maintenance costs for the UKEMS infrastructure (an overhead catenary-based infrastructure for the UK). It is assumed that the maintenace costs percentage remains constant over the years.	

Table 19. From pound to euro -factor

From pound to euro			Source
1 pound		1.13 euro	Guagenti 2023

Tax related data

Table 20. Tax on fossil fuels related data

Data relevant for the refund of the excise duty.	
Energy content of diesel	36 MJ/L
Energy content of biodiesel	33 MJ/L
Difference in energy content with equivalent motor fuel (rounded)	8 %
Minimum quantity per 1,000 L of fuel	109 L
Refund is only received if the proportion of the biocomponent exceeds a specified minimum quantity. The minimum quantity for biodiesel is 109 L / 1000 L (Belastingdienst, 2023b). In this study it is assumed that the transport road transport companies are aware of tax advantage and will therefore use a blended mix of at least this minimum quantity in order to receive the refund. The refund is a cost for society.	

E. Emission-factors for different energy carriers for heavy-duty vehicles

Table 21. WTW-emission factors by type of HDV

WTW-emissions	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Line of reasoning	Source
Diesel Euro VI	1186 g/km	0.08 g/tkm	0.059 g/km	2.1 g/km	0.005 g/tkm	Index figures for alternative fuels and techniques for tractor-trailer light and heavy (index Euro VI = 100) are shown in this table. The percentages are relative to the diesel Euro VI index figure, except for diesel itself. The numbers of SO_x and PM_{sl} for diesel, are taken from the figures for Long Heavy-Vehicles. For electric and hydrogen no air pollutant emissions are assumed in the report of Klein et al. (2020), therefore in this study the same assumption is made. For biodiesel the WTW-factors of Euro VI of Klein et al., (2020) are included, since these are the most up to date factors that can be find. Remark that there might be a different percentage than 11% of biofuel included in the biodiesel. For biodiesel → For the SO_2-and PM_{sl} emission reduction factor for	Klein et al., 2020
Biodiesel Euro VI (97% FAME, 3% HVO)	16 %	-14.72 % Thus 85.28 %	202 %	111 %	-8.2 % Thus, 91.8 %		
Electric (average mix)	70 %	0 %	48 %	29 %	0%		
Electric (wind/solar)	2 %	0 %	0 %	0 %	0 %		
Hydrogen	80 %	0 %	294 %	59 %	0 %		
Hydrogen (from wind/solar/hydro power electrolysis)	7 %	0 %	0 %	0 %	0 %		
Diesel Plug-in hybride (Euro VI)	97 %		91 %	103 %			Mahate, et al., 2023

						biofuels the % reduction compared to emission without blending of 2030, 11% blended biofuel is taken of SO_2 and PM.	
E-diesel	10%	30 %	30 %	30 %	30 %	For the emission-factors of e-diesel are based on the report of Van Kranenburg et al. (2020) that states that e-diesel could reach zero-emission and that the other emissions could also be low. Since an extra conversion process is required for the production of e-diesel compared to hydrogen, the carbon emission are assumed to be a bit higher.	Van Kranenburg et al. (2020) Tol et al., (2023) Klein et al., (2020)

Table 22. Noise emissions by type of HDV

Noise	Level of noise	Line of reasoning	Source

Diesel heavy-duty truck	80 – 87 dB (A)	In the report an indication of the sound is given, which is created during the operation of a heavy-duty truck with a diesel engine.	Lopatin, 2020
Biodiesel heavy-duty truck	80 – 87 dB (A)	Since the same vehicles can be used for biofuels the level of noise is assumed to remain similar to the diesel heavy-duty trucks.	Lopatin, 2020
Electric heavy-duty	-8 db (A)	For heavy electric trucks a noise reduction of 8 db (A) is found.	Pallas et al., 2015
Hydrogen fuel cell heavy-duty truck	-14 db (A)	For the fuel cell heavy-duty noise, data of a fuel cell bus is used, since a bus is also classified in the article as a HDV. A fuel cell bus produces 87 db(A) with a conventional diesel engine and 73 db(A) with a fuel cell. The noise reduction of 16 % is used as input data.	Sharaf et al., 2014
Hybrid heavy-duty vehicle	-2 db (A)	For a hybrid heavy-duty vehicle a noise reduction between 1 – 3 db (A) is found, depending on the speed and gear selection. Therefore, an average of 2 db (A) noise reduction is assumed in this study.	Pallas et al., 2015
E-fuel truck noise	80 – 87 dB	Since the same vehicles can be used for biofuels the level of noise is assumed to remain similar to the diesel heavy-duty trucks.	Tol et al., 2023; Lopatin, 2020

F. Valuation of effects

Table 23. Environmental prices for emissions

	Scenario-Below	Scenario-Central	Scenario-Above	Line of reasoning	Source
CO_2	€ 0.50	€ 0.130	€ 0.160	These are the environmental prices for air pollutant emissions in the Netherlands, in €/kg in 2021. There is a below-, central- and above variant for the prices stated in de Bruyn et al. (2023). Since PM_v is the abbreviation for PM_{10} by combustion and PM_{sl} is the abbreviation for PM_{10} due to wear, for both PM_v and PM_{sl}, the factors of PM_{10} are used.	de Bruyn et al., 2023 Klein et al., 2020
SO_2	€ 33.7	€ 57.5	€ 83.1		
PM_v (PM_{10})	€ 41.4	€ 69.3	€ 97.9		
NO_x	€ 18.3	€ 29.9	€ 44.1		
PM_{sl} (PM_{10})	€ 41.4	€ 69.3	€ 97.9		
Noise 70 - 75 db (A)	€ 1498	€ 1683	€ 1861	Since noise is considered as a negative effect for humans due to health complaints, production loss or nuisance caused by road freight trucks, noise-emissions are perceived as a cost. The environmental prices for road	
Noise 75 - 80 db (A)	€ 2069	€ 2276	€ 2489		de Bruyn et al., 2023
Noise 80+ db (A)	€ 2450	€ 2670	€ 2906		

				traffic noise exposure, for 2021, are in euro per person per year. Defined for the level of noise in dB (A). Thus, X euro per year for amount of persons that suffer the noise level above Z db(A).	

G. Fleet development per strategy

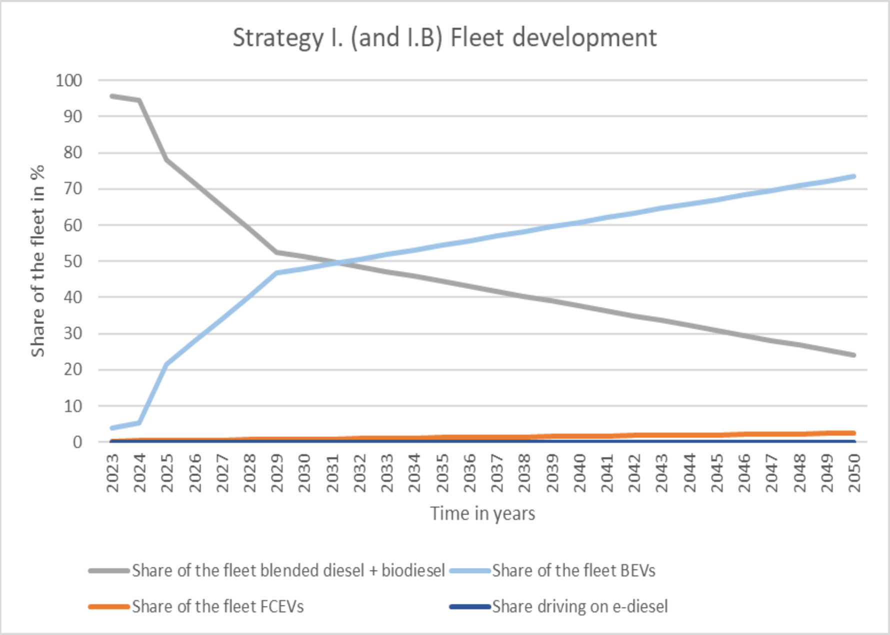


Figure 36. Fleet development of strategy I. (and I.B)

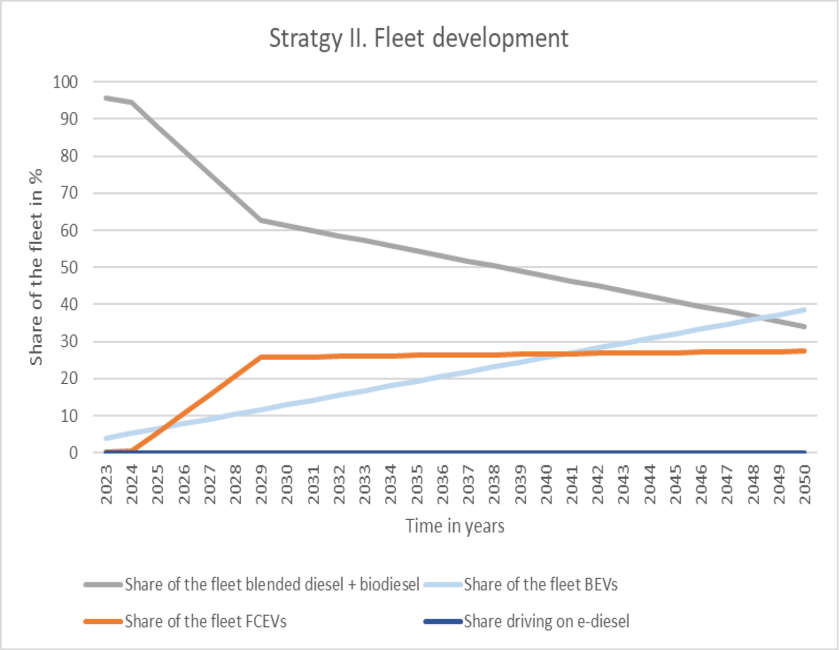


Figure 37. Fleet development of strategy II

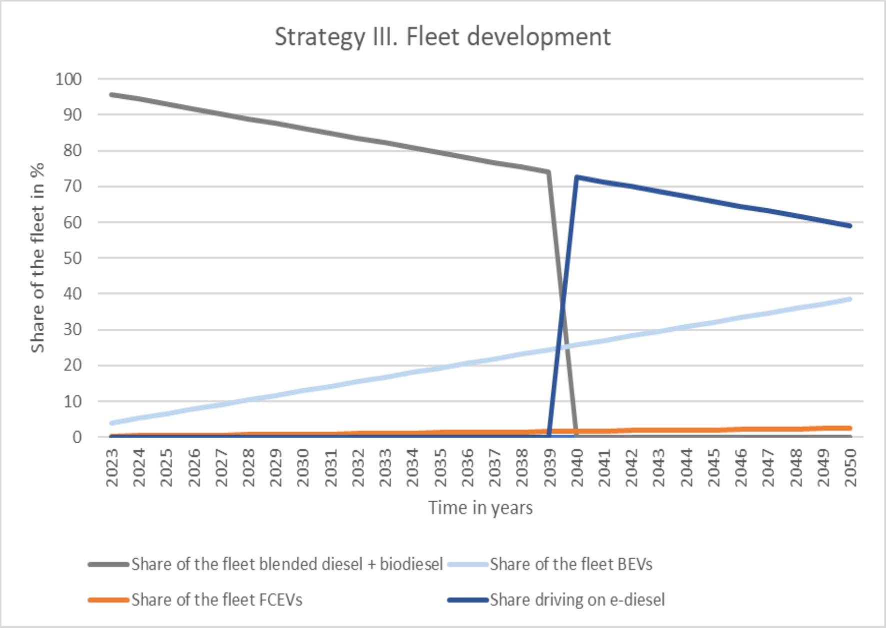


Figure 38. Fleet development of strategy III.

H. Development of emissions per strategy

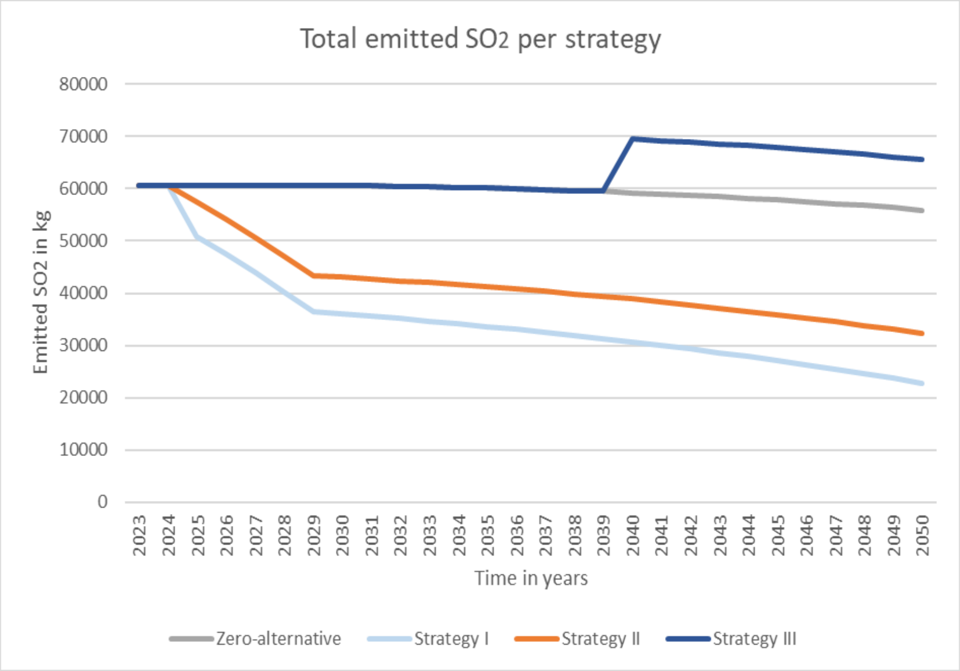


Figure 39. Total emitted SO_2 per strategy

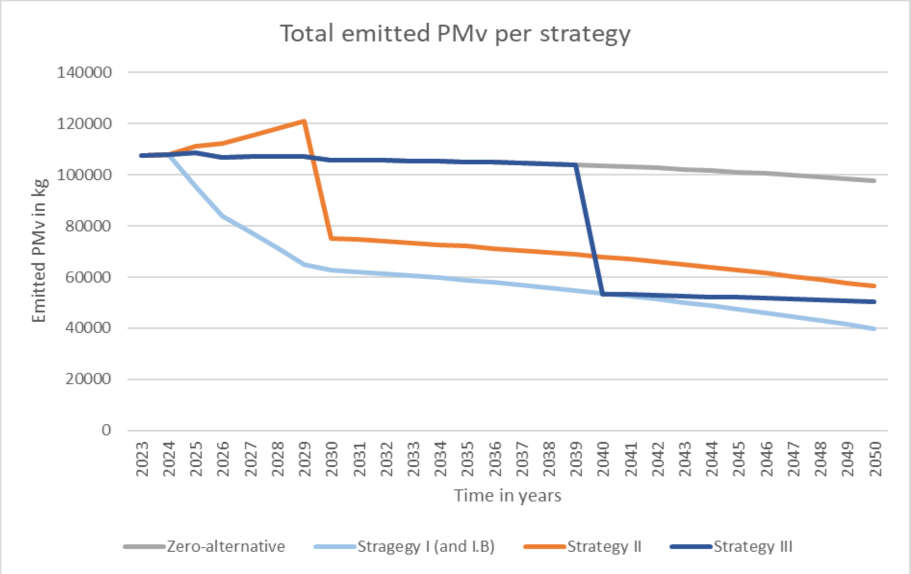


Figure 40. Total emitted PM_v per strategy

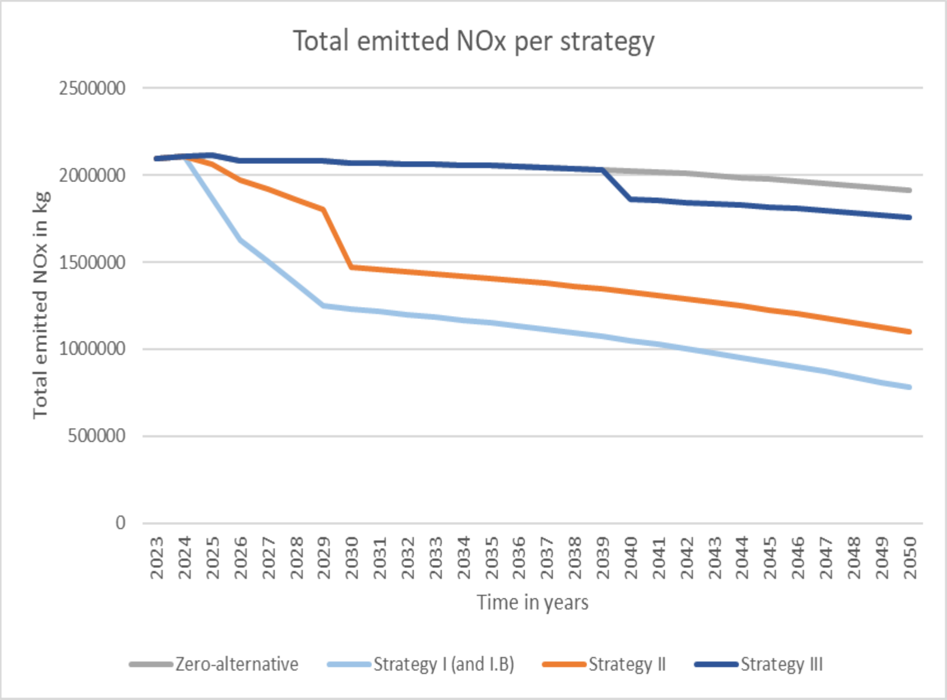


Figure 41. Total emitted NO_x per strategy

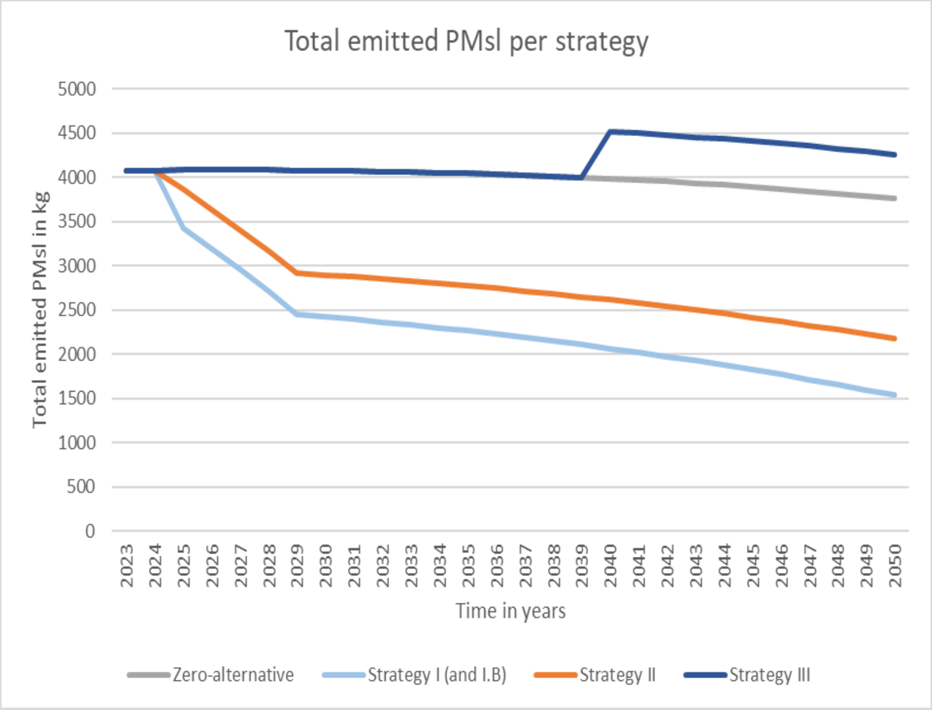


Figure 42. Total emitted PM_{sl} per strategy

I. Costs and benefits per category

Table 24. Results for environmental costs

Type of strategy Environmental costs [euro]	I. A. Stimulation BEVs	I. B. Stimulation BEVs + CERS	II. Stimulation FCEVs	III. Mandatory biofuels until 2040 and after e-diesel
(Avoided) costs emitted CO$_2$-emissions	140,000,000	140,000,000	-27,000,000	53,000,000
(Avoided) costs total emitted SO2-emissions	28,000,000	28,000,000	28,000,000	15,000,000
(Avoided) costs total emitted PMv emissions	59,000,000	59,000,000	46,000,000	40,000,000
(Avoided) costs total emitted NOx-emissions	496,000,000	496,000,000	456,000,000	291,000,000
(Avoided) costs total emitted PMsl-emissions	2,000,000	2,000,000	2,000,000	1,000,000

Table 25. Results for producer-surplus

Type of strategy Difference producer-surplus	I.A. Stimulation BEVs	I. B. Stimulation BEVs + CERS	II. Stimulation FCEVs	III. Mandatory biofuels until 2040 and after e-diesel
Increase producer-surplus for existing purchase BEVs	64,000,000	64,000,000		
Increase producer-surplus for existing purchase FCEVs			7,500,000	
Increase producer-surplus for new purchase BEVs	562,000,000	562,000,000		
Increase producer-surplus for new purchase FCEVs			1,058,000,000	

Increase producer-surplus new recharging station	2,000,000	2,000,000		
Increase producer-surplus new hydrogen station			7,500,000	
Increase producer-surplus pantograph system		24,000,000		
Increase producer-surplus CERS		271,000,000		

Table 26. Results costs for loss of tax on fossil fuels

Type of strategy **Tax costs**	**I. A. Stimulation BEVs**	**I. B. Stimulation BEVs + CERS**	**II. Stimulation FCEVs**	**III. Mandatory biofuels until 2040 and after e-diesel**
(Missed) excise from blended diesel + biodiesel vehicles	-1,349,000,000	-1,349,000,000	-939,000,000	-1,081,000,000
Refund excise from blended diesel+ > 10,9 % biodiesel	12,000,000	12,000,000	8,500,000	10,000,000

J. Results sensitivity analysis

Table 27. Results sensitivity analysis

Change in NPV of strategy ->	**Strategy I.A**		**Strategy I.B**		**Strategy II**		**Strategy III**	
Input variable	**- 10%**	**+10%**	**- 10%**	**+10%**	**- 10%**	**+10%**	**- 10%**	**+10%**
Average number of trucks	29	-29	17	-17	24	-23	11	-11
Fleet growth factor	3	-3	2	-2	3	-2	1	-1
Working days	20	-20	12	1	15	-13	11	-11
Average driving time a day	20	-20	12	-12	14	-14	11	-11
Average speed for a truck	20	-20	12	-11	14	-14	11	-11
Total distance driven year 1	0	0	1	1	0	0	0	0
2050 Share of trucks driving on battery electric	0	0	-4	5	0	0	-1	1
2020 Diesel truck purchase costs	-6	-1	-3	4	0	0		
2020 Battery electric truck (400 kWh) purchase costs	8	-8	5	-4				
2050 Diesel truck purchase costs	0	0	1	1	-6	6		
2050 Battery electric truck (400 kWh) purchase costs	3	0	1	1				
2020 purchase costs FCEV					42	42		
2050 purchase costs FCEV					35	35		
Investment costs recharging station	0	0	0	1				
Hydrogen station					0	0		
Excise duty for 100%diesel	52	-47	31	-30	49	-49	35	-35
Energy content of diesel	0	0	1	1	0	0	0	0
Energy content of pure biodiesel	0	0	1	1	0	0	0	0
Amount of biodiesel required to get the refund	-6	6	1	1	-5	5	-4	4
Average fuel consumption - HDV 100%diesel	7	7	1	1	-5	5	0	0
Diesel								
WTW CO2 emission factor	0	0	-4	6	-12	12	0	0
WTW SO2 emission factor	0	0	0	1	-1	1	0	0
WTW PMv emission factor	0	0	0	1	-2	2	0	0
WTW NOx emission factor	0	0	-11	12	-19	19	0	0
WTW PMsl emission factor	0	0	0	1	0	0	0	0
biodiesel Euro VI								
WTW CO2 emission factor	-6	8	-4	4	-6	7	-5	5
WTW SO2 emission factor	5	9	0	1	-1	1	-1	1
WTW PMv emission factor	-13	26	-1	2	-2	2	-1	12

WTW NOx emission factor	7	7	-11	12	-18	18	-2	-1
WTW PMsl emission factor	-6	8	0	1	0	0	-2	-1
Battery electric (average mix)								
WTW CO2 emission factor	7	8	0	1				
WTW SO2 emission factor	7	7	0	0				
WTW PMv emission factor	7	7	0	0				
WTW NOx emission factor	7	7	1	1				
WTW PMsl emission factor	7	8	0	1				
(BEV solar/wind)								
WTW CO2 emission factor	6	8	1	1				
WTW SO2 emission factor	0	0	0	0				
WTW PMv emission factor	0	0	0	0				
WTW NOx emission factor	0	0	0	0				
WTW PMsl emission factor	0	0	0	0				
Valuation of environmental effects - data								
CO2 valuation	10	4	3	-2	0	0		
SO2 valuation	7	6	1	0	0	0		
PMv valuation	8	5	1	0	0	0		
NOx valuation	19	-6	8	-7	0	0		
PMsl valuation	7	7	-7	-7	0	0		
Discount factor in year X	7	7	-10	11	-17	17		
Pantograph costs in euro			11	11				
Catenary Electric Road System costs (pound)			11	11				
FCEV mix								
WTW CO2 emission factor					0	0		
WTW SO2 emission factor					0	0		
WTW PMv emission factor					0	0		
WTW NOx emission factor					0	0		
WTW PMsl emission factor					0	0		
FCEV (solar/wind)								
WTW CO2 emission factor					0	0		
WTW SO2 emission factor					0	0		
WTW PMv emission factor					0	0		
WTW NOx emission factor					0	0		
WTW PMsl emission factor					0	0		
E-diesel								
WTW CO2 emission factor							-1	-1
WTW SO2 emission factor							-1	-1
WTW PMv emission factor							-1	-1
WTW NOx emission factor							-1	-1