Towards a Sustainable Transport Sector: Assessing the Implications of Transitioning to Hydrogen Fuel Cell Trucks

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A Social Cost-Benefit Analysis of Subsidy Programs for Hydrogen Fuel Cell Heavy-Duty Trucks in the Dutch Long-Haul Transport Sector

By

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Executive summary

The transport sector in the Netherlands accounts for roughly 12% of the country's emissions and must significantly decrease to meet the targets set in the Paris Agreements. A promising alternative involves implementing hydrogen fuel cell heavy-duty trucks for covering long distances, offering an emission-free solution when produced through renewable sources such as solar or wind energy. Despite the growing interest in the implementation of hydrogen in the transport sector, existing literature primarily addresses either the financial costs or the technological challenges of hydrogen trucks. This leaves a noticeable gap regarding the consideration of the social effects of hydrogen freight transport subsidies, which are essential to provide a comprehensive evaluation of the viability and impact of adopting hydrogen fuel cell heavy-duty trucks.

This thesis aims to address this gap by examining both the social costs and benefits of subsidizing hydrogen fuel cell heavy-duty trucks in the Netherlands, offering a perspective on the potential implications for the transport sector and society. The goal of this thesis is to conduct a Social Cost-Benefit Analysis to evaluate the social viability of a subsidy program aimed at transitioning diesel heavy-duty trucks to hydrogen in the Netherlands. This program covers the total cost of ownership difference between diesel and hydrogen fuel cell heavy-duty trucks. Achieving this goal provides insights and recommendations for policymakers concerning the transition to hydrogen fuel cell trucks in the long-haul transport sector. The research question of this thesis is:

> What is the social cost-benefit ratio of policies that aim for the widespread adoption of hydrogen fuel cell heavy-duty trucks in the year 2050 in the Netherlands?

This thesis used a mixed-methods approach involving interviews with key stakeholders, including representatives from RVO, the Municipality of Infrastructure and Water Management, and Heisenkamp, a leading transport company in the Netherlands. These interviews provided valuable insights into the potential adoption of hydrogen fuel cell heavy-duty trucks and the associated challenges and opportunities from the perspective of the policymakers and the truck owners. Also, a comprehensive data analysis was conducted to gather data on the total cost of ownership of hydrogen heavy-duty trucks and the social effects of transitioning towards hydrogen.

A Social Cost-Benefit Analysis estimates the social viability of the subsidy program by comparing the costs of subsidy and infrastructure with the social effects, expressed in euros, regarding the null alternative. Here, the null alternative represents the anticipated outcome under existing rules and regulations. The measured social effects include emission reduction (CO_2, NO_x, $PM_{2.5}$, and PM_{10}) and the social gain from the perspective of the truck owner who receives the subsidy.

This thesis uses two null alternatives, depending on the future market share of hydrogen fuel cell heavy-duty trucks. In one scenario, hydrogen fuel cell heavy-duty trucks are projected to cover trips exceeding 50 kilometers, capturing a market share of 60%. In the second scenario, targeting trips exceeding 150 kilometers, hydrogen fuel cell heavy-duty trucks are estimated to hold a market share of 25%. The remaining share is presumed to be covered by electric heavy-duty trucks, as they are more cost-effective on shorter distances.

This thesis analyses three subsidy programs, covering the total cost of ownership difference between hydrogen fuel cell and diesel heavy-duty trucks, differing in their implementation dates (2024, 2030, and 2040). The Social Cost-Benefit Analysis extends until 2050.

The total cost of ownership of a hydrogen fuel cell heavy-duty truck varies over time, as economies of scale are expected to decrease the fixed cost of the hydrogen fuel cell heavy-duty truck, and the fuel price of hydrogen. Depending on the starting date of the subsidy program, these economies of scale can be accelerated.

The results of this Social Cost-Benefit Analysis show that initiating the subsidy program at the earliest opportunity (2024) provides the most favorable outcome, primarily because emission reduction leads to long-term social gains. Initiating the subsidy program in 2024 results in a Net Present Value of 2.4 and 1.8 billion euros for the 50+km and 150+km alternatives, respectively. Delaying the subsidy program to 2030 or 2040 leads to negative Net Present Values, making it socially unviable.

Initiating the program in 2024 incurs the highest subsidy costs, estimated at 4 billion euros for the 150km+ scenario and 12 billion euros for the 50km+ scenario, despite yielding the most favorable Net Present Value. This significant cost arises from the notable difference in total ownership costs between diesel and hydrogen fuel cell heavy-duty trucks during the initial years, leading to a subsidy requirement that exceeds the Dutch government's proposed budget of 200 million euros.

The model's outcome is significantly affected by the fluctuating prices of diesel and hydrogen fuel, as well as the retail prices of hydrogen trucks. Should hydrogen fuel and hydrogen fuel cell heavy-duty truck retail prices not meet anticipated levels due to assumed economies of scale, the Social Cost-Benefit Analysis results will be negative across all scenarios, requiring substantial subsidies regardless of diesel price developments.

This thesis demonstrates that under specific assumptions regarding economies of scale, resulting in reduced retail prices for hydrogen fuel cell heavy-duty trucks and lower fuel costs for hydrogen in the future, a favorable Net Present Value can be achieved for a subsidy program supporting heavy-duty hydrogen fuel cell trucks. These assumptions, although speculative, draw from a diverse body of literature, lending credibility to the potential outcome despite its assumption-based nature. For the Dutch government to initiate this subsidy program in a socially viable manner, prompt action is needed, accompanied by a substantial increase in budget readiness.

However, two significant uncertainties require further investigation before starting this subsidy program. Firstly, there is uncertainty surrounding infrastructure costs, where this thesis currently only considers the procurement and installation of fuel stations, overlooking potential additional expenses associated with establishing a hydrogen infrastructure, such as pipeline reinforcement. Secondly, it pertains to the scale of assumptions regarding economies of scale, which wield considerable influence on the outcome and necessitate deeper exploration. Both subjects demand further scrutiny for a more precise understanding and to achieve a more accurate Net Present Value.

Contents

List of abbreviations

HDT – Heay-Duty Truck
FC – Fuel Cell
NPV – Net Present Value
CBA – Social Cost-Benefit Analysis
TCO – Total Cost of Ownership
IRR – Internal Rate of Investment

Please note that these abbreviations are not used in research questions, chapter titles, conclusions, tables and figures

1 Introduction

1.1 Problem statement

The Paris Agreement's main goal is to combat climate change by aiming to limit global temperature rise to well below 2 degrees Celsius, with a particular focus on staying below 1.5 degrees Celsius (United Nations, 2016). In alignment with this goal, the Dutch government has established targets to address climate change. These targets include achieving a 55% reduction in net greenhouse gas emissions by 2030 compared to 1990 levels, with the overarching objective of attaining carbon neutrality by 2050. The transport sector, in the Netherlands, stands as a significant contributor to overall greenhouse gas emissions, responsible for approximately 12% of the nation's total emissions (CBS, 2022).

The emissions from Heavy-Duty Trucks (HDT) within the transport sector significantly outweigh those from other vehicles (CBS, 2022). While smaller vehicles are increasingly transitioning to electrification, HDTs lag in this development. The electrification of HDTs, especially for longer distances, presents challenges primarily related to battery weight issues (Liimatainen, 2019). To achieve carbon neutrality by 2050 in the entire transport sector, policymakers need to actively pursue and implement emission-free alternatives for long-haul HDTs.

One promising alternative for long-distance transportation is the hydrogen Fuel Cell (FC) HDTs, which utilize hydrogen as fuel instead of fossil fuels, offering the potential for long-distance travel without the weight constraints associated with electric HDTs. If hydrogen is produced from renewable sources such as solar and wind, no emissions are emitted. Major truck manufacturer DAF views hydrogen technology as a viable option and was recognized with the Truck Innovation Award in 2022 for their hydrogen FC HDT prototype (DAF, 2023).

Although hydrogen presents a promising emission-free solution for the transport sector, it also brings challenges. One significant challenge is the current higher Total Cost of Ownership (TCO) associated with hydrogen FC HDTs compared to conventional diesel trucks, presenting an economic barrier that complicates the transition for truck owners. By implementing a subsidy program covering the financial difference, the transition of HDTs could be accelerated.

However, to determine the social viability of this program, a comprehensive analysis is necessary to consider not only the costs but also the social gains derived from such acceleration. If policymakers wish to initiate such a subsidy program, it is advisable to do so promptly, as researchers warn that delaying action could result in carbon lock-in, further complicating the transition process of HDTs (Aryanpur & Rogan, 2024).

1.2 Research objective

The aim of this thesis is to assess the social viability of a subsidy program designed for hydrogen FC HDTs. By accomplishing this goal, policymakers can make more informed decisions regarding financial support for the long-haul heavy-duty transport sector. The research question guiding this MSc thesis is:

> What is the social cost-benefit ratio of policies that aim for the widespread adoption of hydrogen fuel cell heavy-duty trucks in the year 2050 in the Netherlands?

To delve into this question effectively, a comprehensive grasp is needed of the existing literature. Therefore, the following chapter will conduct a literature review that evaluates various papers on hydrogen technology developments, the economics of hydrogen in the transport sector, and current analyses that consider both the financial costs and social benefits of hydrogen policy implications. This review aims to identify gaps in the literature that this thesis intends to address.

1.3 Sub-questions

The primary objective of this research is to assess the social viability of a subsidy program for hydrogen FC HDTs. To address the main research question concerning the social cost-benefit ratio of the program, four sub-objectives are established, each aligned with specific sub-questions.

The first objective is to identify and understand the effects associated with the implementation of a subsidy program and the transition to hydrogen HDTs. To achieve this, it is imperative to examine the financial, technical, and social effects of deploying HDTs in the Netherlands. This exploration will offer insights into both the costs and benefits associated with the subsidy program. The first sub-question is:

SQ1: What are the financial, technical, and social effects of the implementation of hydrogen fuel cell heavy-duty trucks in the Netherlands?

The second objective of this research is to identify the current rules and regulations affecting the transport sector, representing the null alternative scenario where no new policy intervention would occur. These findings will serve as the foundation for comparing policy interventions against the null alternative. The second sub-question is:

SQ2: What is the null alternative of the analysis?

The third objective aims to identify the disparity between the null alternative and the policy intervention. Understanding the effects of both options enables the establishment of their distinctions. The third sub-question is:

SQ3: How does the policy alternative differ from the null alternative?

The final objective is centered on determining the unit of effects for both the null alternative and the policy alternative. The aim is to identify differences in a measurable unit to enable an objective comparison between the alternatives and assess the social feasibility of the policy alternative. The fourth sub-question is:

SQ4: How can the social effects of implementing a subsidy program for hydrogen fuel cell heavy-duty trucks be valued in the Social Cost-Benefit Analysis?

1.4 Relevance

This research holds significant societal relevance as it addresses pressing sustainability challenges within the transport sector. By considering both the financial and social implications of introducing hydrogen FC HDT, this study aims to inform decision-makers, shape policy developments, and influence industry practices toward achieving more sustainable transportation solutions.

Furthermore, from a scientific perspective, this research contributes by bridging the gap between technical advancements, financial considerations, and social impacts. By examining decision-making processes in complex socio-technical environments, this study aims to advance our understanding of innovation dynamics within the heavy-duty transport sector.

Lastly, within the context of CoSEM, this research project addresses the complexities of decision-making within systems characterized by social dilemmas and technological uncertainties. By analyzing the interplay between various stakeholders and technologies, this study contributes to the broader discourse on navigating uncertainties in socio-technical systems.

1.5 Structure

The structure of the thesis is organized as follows: Chapter 2 reviews the existing literature and identifies the knowledge gap addressed in this study. In Chapter 3, the methodology, including research design and data collection methods, is outlined. Chapter 4 delves into the social effects within the research scope, encompassing a financial breakdown of the TCO for hydrogen FC and diesel HDTs, infrastructure costs, and the social benefits of widespread hydrogen adoption. The projection of the null alternative is presented in Chapter 5, illustrating the expected outcome based on current regulations without additional policy interventions. Chapter 6 examines the results of the Social Cost-Benefit Analysis (CBA), providing the Net Present Value (NPV) for all three subsidy programs. A sensitivity analysis in Chapter 7 investigates influential variables, which are then used in Chapter 8 for scenario analysis to offer policymakers various potential outcomes to enhance their decision-making. Subsequently, a discussion chapter evaluates the model's strengths and weaknesses. Finally, the conclusion presents recommendations for policymakers and suggestions for future research.

2. Theoretical background

This chapter provides an in-depth exploration of existing literature to develop a comprehensive understanding of the research topic. Through a thorough literature review, attention is focused on three critical areas relevant to the study: the technology and economics of hydrogen FC HDTs, as well as the social implications of policies related to hydrogen in the transport sector. By synthesizing and analyzing the body of research in these areas, this literature review aims to establish the current state of knowledge, identify gaps, and lay the groundwork for the subsequent analysis and discussion. The method that was selected for this study is the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) approach. The database that was used for this literature review is Scopus. The search strings and their results are presented in Table 1.

Table 1: *Search string and result.*

Search strings	**Results (N=)**
Hydrogen AND fuel AND cell AND technology AND heavy AND duty AND vehicles AND transport	46
Hydrogen AND transport AND social AND cost AND benefit	36
Heavy AND duty AND truck AND social AND cost AND benefit	14

The PRISMA method comprises four distinct phases: identification, screening, eligibility assessment, and inclusion. Initially, duplicate papers from different search strings were excluded. Subsequently, papers underwent screening based on their title and abstracts. The last step involved a comprehensive reading of the papers to make the final selection. The result of the PRISMA method is the selection of 17 papers that were used in the literature review are shown in Figure 1.

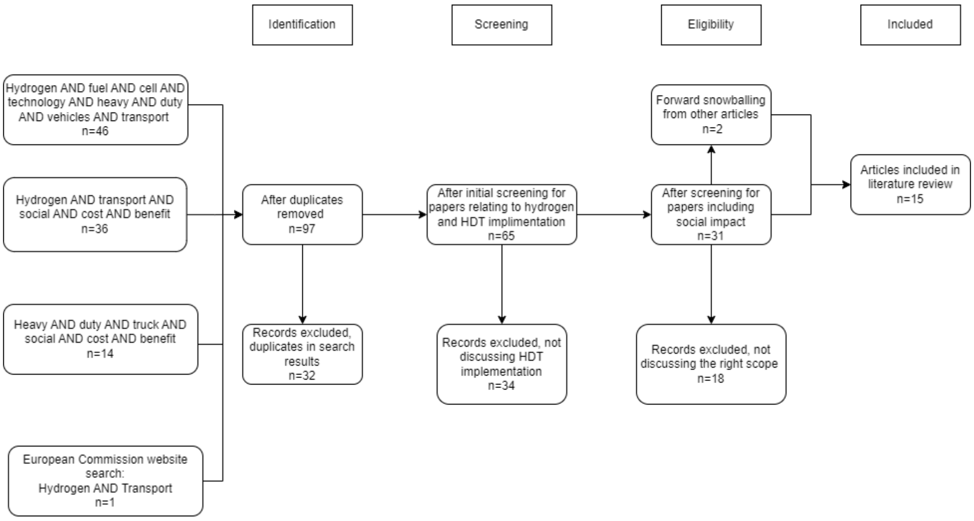

Figure 1: *PRISMA.*

2.1 Literature review

The technology of hydrogen heavy-duty trucks

As the transport sector seeks to reduce its carbon footprint, various zero-emission alternatives are being explored. Among these alternatives, hydrogen has attracted increasing attention as a promising energy source. Hydrogen offers the advantage of being producible from renewable sources such as solar and wind, thereby eliminating greenhouse gas emissions (Singla, 2022). Vehicles can employ Fuel Cells (FC) to utilize this green hydrogen as fuel. A hydrogen FC uses hydrogen to produce electricity and heat to power the engine and to generate force to drive a vehicle (Department of Energy, 2022).

Electric vehicles are also emerging as a viable zero-emission alternative in the transport sector. Battery-electric trucks are currently favored for short trips due to their cost-effectiveness in meeting CO_2 reduction targets (Basma, 2023). However, their practicality decreases with longer distances due to battery-weight constraints, making hydrogen a more favorable option for long-haul Heavy-Duty Trucks (HDT). Unlike electric HDTs, hydrogen FC HDTs offer the advantage of quick refueling, similar to diesel HDTs, thus avoiding the time-consuming recharging process that can strain local grids near logistics centers and rest stations (Liimatainen, 2019).

For hydrogen to serve as an emission-free alternative, it must be generated from renewable sources rather than fossil fuels. Currently, most of the hydrogen is produced using the steam reforming method, a cost-effective approach reliant on fossil fuels (Megía, 2021). Utilizing fossil fuels for hydrogen production significantly increases CO_2 emissions, with an estimated generation of approximately 10 kg of CO_2 per 1 kg of H2 produced (Kothari, 2008). Europe is determined to boost green hydrogen production, as outlined in the European Commission's 2020 plan, creating a promising outlook for emission-free hydrogen FC HDTs.

Economic of hydrogen trucks

The primary challenge of hydrogen FC HDT is the higher Total Cost of Ownership (TCO) compared to their conventional diesel counterparts. These costs are typically divided into three categories: the expense of acquiring a hydrogen FC HDT, the cost of hydrogen as a fuel source, and the expenditure on the necessary infrastructure. Presently, the price of a hydrogen FC HDT remains considerably higher than that of traditional diesel trucks. Anticipated reductions in the future costs of hydrogen FC HDTs vary among scholarly perspectives, underscoring the uncertainty surrounding the price development (Aminudin, 2023). However, Plotz highlights that the uncertainty surrounding the future costs of hydrogen FC HDT poses a significant challenge. Postponing the commencement of mass production for these trucks in an attempt to reduce costs could diminish the likelihood of their success in future low-carbon road transport (Plötz, 2022).

Currently, hydrogen production from renewable sources is more costly than that from fossil fuels, making hydrogen fuel notably more expensive than diesel fuel. However, there is an expectation that the price of green hydrogen will decrease over time, eventually becoming economically competitive with conventional hydrogen sources. Nonetheless, this projected decline in cost is subject to uncertainty, as noted in Zhou's analysis in 2022.
Finally, in terms of hydrogen infrastructure, a portion of the existing gas grid can be repurposed for hydrogen transport. While this repurposing effort may help alleviate some hydrogen transport costs, uncertainties persist regarding the impact of hydrogen on infrastructure, including pipeline assets, corrosion, and maintenance (Lipiäinen, 2023). Moreover, the levelized cost of refueling stations varies widely, making it difficult to predict the future price of hydrogen fueling (Wu., 2024).

Social effects

This literature review provides insights into the technological advancements and cost considerations associated with hydrogen FC HDTs, emphasizing their potential as a sustainable transportation alternative. However, while studies have extensively examined the technical feasibility and economic viability, they overlooked critical social considerations.

Social effects, an issue raised by Joshi (2023), often go unaddressed when assessing the costs and benefits of implementing new transportation technologies. Historically, scientists have stressed the importance of factoring social benefits when considering the implementation of hydrogen-based solutions. Holt, for example, has highlighted the limitations of the market price system, which tends to overlook a wide range of societal costs, including emissions and economic vulnerabilities, thereby hindering the adoption of socially beneficial alternatives (Holt, 1978).

Recent research has started to delve into the social aspects of hydrogen integration in transportation, aiming to fill this gap. Razm (2024) conducted a techno-economic analysis, exploring the potential emission reductions and economics of hydraulic fracking processes for heavy-duty vehicles. While demonstrating potential emission reductions, this study overlooked any policy implications.

In a study by Alamoodi et al. (2024), a CBA was employed to assess various types of buses for sustainable public transportation, including hydrogen buses. The findings indicated that hydrogen buses were deemed non-viable due to their significant costs. Although this paper evaluated different policies, it primarily focused on buses rather than heavy-duty vehicles.
Furthermore, Almaraz et al. (2022) examined social cost-benefit optimization for a hydrogen supply chain in Hungary, even highlighting the scarcity of studies considering economic, environmental, and social aspects simultaneously.

2.2 Knowledge gap

Despite extensive research into technological advancements and cost considerations, there is still a notable lack of attention given to the broader social impacts of hydrogen FC HDT. Existing studies often neglect these social effects, thereby missing a comprehensive assessment crucial for understanding the broader implications of widespread hydrogen implementation.

The identified knowledge gap is crucial for understanding the implications of transitioning to hydrogen FC HDTs. Filling this gap will achieve the objective of this study, which aims to evaluate the social viability of a subsidy program to accelerate the transition to hydrogen. Through an integrated assessment of technical, financial, and social dimensions, this research seeks to provide policymakers and stakeholders with a comprehensive understanding of the implications associated with adopting hydrogen FC HDTs.

By addressing the identified knowledge gap in the literature, this research serves as a critical stepping stone toward a more comprehensive understanding of the implications of transitioning to hydrogen FC HDT. Integrating social factors into the assessment of hydrogen adoption not only enhances our understanding of the broader societal implications but also provides valuable insights for policymakers and stakeholders, enabling them to make informed decisions. Ultimately, filling this gap will not only advance knowledge in the field of sustainable transportation but also contribute to addressing real-world challenges and informing policy and practice.

3. Methodology

This chapter outlines the research design, data collection methods, and analysis techniques utilized to evaluate the social implications of transitioning to hydrogen adoption in the transportation sector. Through transparent reporting and thorough analysis, this chapter aims to provide valuable insights to guide evidence-based policy decisions.

3.1 Research design

As the research objective is to evaluate a policy intervention, a quantitative descriptive approach is deemed appropriate as it enables the production of precise and measurable data without requiring direct intervention by the researcher (Williams, 2011). This method allows for the collection and analysis of numerical variables systematically, providing valuable insights into the effectiveness of the subsidy program. While the quantitative descriptive approach offers the advantage of avoiding direct manipulation of variables and instead focuses on describing the sample and variables (Siedlecki, 2020), it is essential to acknowledge its limitations. Quantitative methods, though precise, may not delve as deeply as qualitative research methods, potentially overlooking important nuances and perspectives (Rahman, 2020). Recognizing the quantitative approach's limitations in capturing nuanced perspectives, this thesis will use a Social Cost-Benefit Analysis (CBA) to better understand the subsidy program's social implications.

A CBA serves as an informative tool for guiding policy decisions by providing an objective assessment of the social implications of a policy measure or option (Koopman, 2016). This analysis involves calculating both the social costs and benefits associated with a policy, allowing policymakers to weigh the overall impact on society. CBA aims to ensure that policy decisions are grounded in objective considerations to the greatest extent possible. However, it's important to note that CBA is often incomplete due to the inherent challenge of valuing all social costs, which can limit its effectiveness (Mouter, 2013). Nevertheless, this thesis is committed to addressing these challenges through transparent reporting of variables and sources, sensitivity analysis to assess parameter influences, and scenario analysis to enhance effectiveness and robustness. This thesis adheres to the CBA guidelines established by the PBL Netherlands Environmental Assessment Agency (2022), which are widely used to evaluate policies across the Netherlands. These guidelines ensure consistency and reliability in policy analysis, making them appropriate for this study.

3.2 Data collection method

For data collection, two methods are used to gather information relevant for this thesis. Intensive desk research will be conducted to find the current rules and regulations, input variables and other trends. This intensive desk research is conducted by looking at published papers and reports. The published papers are found using Scopus and Google Scholar. Scopus is mainly used for the literature review, to establish a broad understanding of the existing literature surrounding hydrogen implementation in the transport sector.

Later on, Google Scholar was employed to specifically search for individual input variables required for the CBA. If these variables were not available in published papers, additional scrutiny was directed towards reports.

These reports are preferably sourced from governmental websites, with a preference for platforms like the European Commission’s website, to access up-to-date rules and regulations concerning emission reduction in both Europe and the Netherlands. Otherwise, reports were found individually by using Google. Due to the potential variation in reliability, each source was carefully assessed for credibility and trustworthiness. On numerous occasions, variables presented a range of possible outcomes rather than a single static value. In such cases, either the average or most likely outcome was selected. All variables used in this CBA are detailed in Appendix A, along with their respective values and sources, therefore enhancing transparency.

Secondly, qualitative interviews were conducted with experts to a gain deeper understanding of hydrogen implementation in the Netherlands. Representatives from the RVO, the Municipality of Infrastructure and Water Management, and Heisenkamp, a prominent transport company, were interviewed. These three interviews aimed to provide a comprehensive understanding of the challenges and opportunities associated with introducing hydrogen in the long-haul transport sector. The Municipality of Infrastructure and Water Management was selected to represent policymakers, offering insights into decision-making processes and relevant considerations. Heisenkamp was chosen to provide perspectives from truck owners, shedding light on their willingness to transition to alternative fuels. Finally, RVO served as an objective third party, validating insights gathered from previous interviews and contributing to a more comprehensive and impartial understanding of the issue.

As the interviews were qualitative in nature, they focused on gathering insights and perspectives rather than numerical data. This approach allowed for a multifaceted understanding of the issue by capturing diverse viewpoints. Since the interviews were conducted in a qualitative format, no statistical analysis was applied to the interview data. Instead, the focus was on capturing nuanced insights and subjective interpretations to enrich the overall analysis.

3.3 Analysis techniques

The collected data will be utilized to develop a model in Excel for analysis purposes. This model will integrate all identified social costs and benefits associated with both the null-alternative and the proposed policy interventions. It will facilitate the calculation of the social viability of the policy interventions, projecting costs and benefits from 2024 to 2050, with an annual discount rate of 2.25% applied. This discount rate aligns with the standard rate recommended in general CBA guidelines (PBL, 2022). The model in Excel is made public, with the ability to change each individual variable for any future research.

Subsequently, a sensitivity analysis will be conducted to identify variables significantly influencing the outcome. These key variables will then be used in a scenario analysis, offering policymakers multiple potential outcomes to enhance their decision-making process.

4. Social effects

This chapter examines the social costs and benefits analyzed in this study. The social costs are divided into two categories: the cost of the subsidy program and the infrastructure costs. The subsidy program is set to cover the TCO of hydrogen FC HDTs and diesel HDTs. The social benefits, on the other hand, are the emission reduction and the social gain from the perspective of the truck owner. The social effects serve as the foundation for calculating the cost-benefit ratio, crucial for assessing the social viability of implementing a subsidy program for hydrogen FC HDTs.

4.1 Social cost

4.1.1 Subsidy

The subsidy program is regarded as a social cost, as it involves the allocation of public funds that could be directed toward other societal activities. The subsidy is set to cover the TCO difference between hydrogen FC and diesel HDTs. The underlying assumption is that if the TCO becomes equivalent for both types of trucks, truck owners will purchase a hydrogen FC HDT over a diesel HDT. The TCO of a HDT is divided into three categories: fixed costs, costs of driving, and maintenance costs.

Fixed cost

The fixed costs are the costs of purchasing a new HDT. For diesel HDTs, the fixed cost is approximately €104,000 (Basma, 2021). The fixed costs for hydrogen FC HDTs vary across different sources, ranging from €300,000 to €700,000. This variability arises because hydrogen FC HDTs are currently only available as prototypes, making it challenging to accurately predict their price. This thesis draws upon a report from H2accelerate, a collaborative European initiative involving 13 partners from both the public and private sectors, to determine the fixed cost. The report investigates economies of scale to establish the fixed cost of a hydrogen FC HDT, considering dynamic factors rather than a static fixed cost (H2accelerate, 2022).

Economies of scale suggest that the cost per hydrogen truck is influenced by the scale of production. Companies benefit from cost advantages when production becomes more efficient, as costs can be distributed over a larger quantity of goods (Silberston, 1972). H2accelerate establishes four economies of scale, corresponding to four types of fixed costs (Table 2). The report from H2accelerate did not define when hydrogen advances in economies of scale. In this thesis, economies of scale are assumed to be determined by the market share of FC HDTs within the long-haul heavy-duty market. The economies of scale, with assumed market share and fixed costs, are shown in Table 2.

Table 2: *Economies of scale with market share and fixed cost per hydrogen fuel cell heavy-duty truck.*[1]

Economies of scale	Market share of hydrogen	Fixed cost per truck
Research and development	0%	€ 534,000
Industrial scale up	5%	€ 346,000
Sustainable growth	20%	€ 220,000
Full industrialization	40%	€ 179,000

The current market share of hydrogen is well below 1% and the fixed cost of hydrogen HDT is therefore set at € 534,000. The market share is based on the price development of electric personal vehicles. Initially, the fixed costs of electric vehicles were substantially higher, but with the current market share of electric vehicles in the personal vehicle market at around 30% (CBS, 2023), these costs have significantly decreased. Since electric vehicles continue to decrease in fixed costs annually, the assumption is that only after achieving a market share of 40%, the hydrogen HDT would be considered fully industrialized. After full industrialization, the fixed costs are assumed to decrease by 0.5% annually due to more efficient production causing a decrease in price. This thesis acknowledges the uncertainty associated with this assumption, recognizing that economies of scale will likely be influenced by external factors such as the global switch to a certain zero-emission vehicle.

Even in full industrialization, the fixed cost of a hydrogen FC HDT remains higher than that of a diesel HDT. This is due to the materials used in a hydrogen FC. Noble metals such as platinum are required within a FC. These noble metals are relatively expensive, and their costs of materials are not declining with an economy of scale (Gallagher, 2023).

Cost of driving

The fuel price of hydrogen has been even more volatile as the prices at the station, varying from 10 to 22 euros/kg in the last two years (CBS, 2023). Insufficient published sources specifically address the evolution of hydrogen fuel prices, although there are papers focusing on the projected cost of hydrogen production. Several sources discuss the expenses associated with producing green hydrogen, produced using renewable energy, yet there is considerable divergence in the anticipated trajectory of fuel prices among these publications. This thesis draws upon multiple scenarios outlined by TNO (2022) to project the development of hydrogen fuel prices. It is assumed that changes in hydrogen production costs will directly impact fuel prices.

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[1] *This Table shows each economies of scale in this analysis, with the corresponding market share of hydrogen fuel cell heavy-duty truck in the long-haul transport market and the corresponding fixed cost.*

However, it is important to acknowledge the uncertainty surrounding these assumptions, as historical data shows significant fluctuations in fuel prices. By basing assumptions on published papers regarding the production of green hydrogen, this thesis aims to minimize speculative estimations. The assumed hydrogen fuel price is shown in Figure 2.

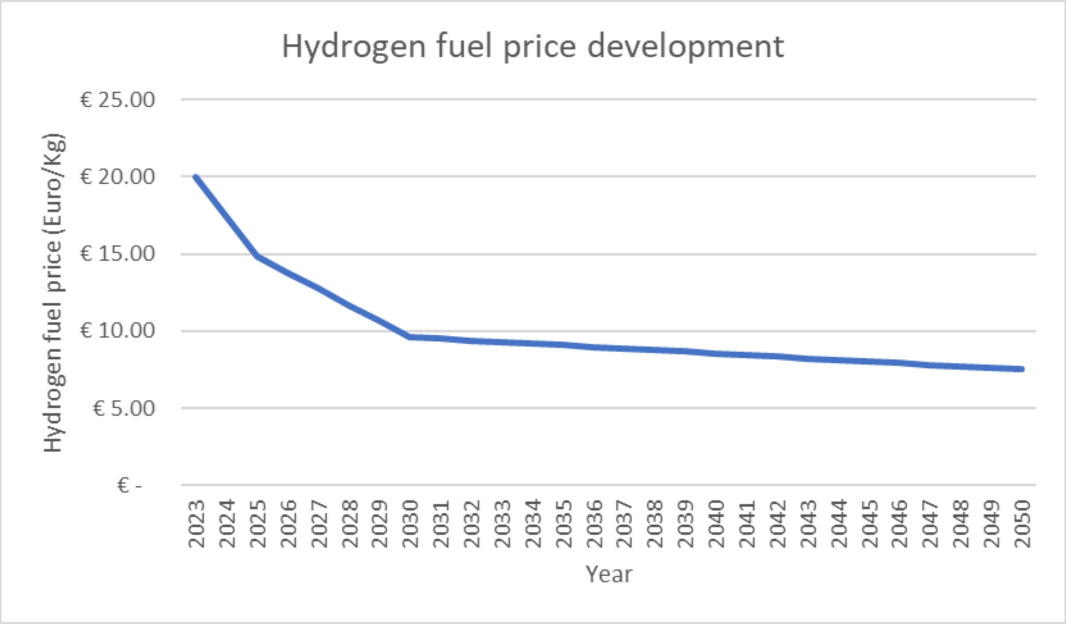

Figure 2: *Development of hydrogen fuel price from 2023 – 2050 in euro/kg (TNO, 2022).*

This thesis operates under the assumption that accelerating the production of hydrogen FC HDTs will lead to lower fixed costs due to economies of scale. Additionally, it anticipates a decrease in the price of hydrogen as demand increases. The thesis assumes that the production of green hydrogen will become more efficient, resulting in a reduction in hydrogen prices. Initiating the subsidy program at the earliest opportunity accelerates economies of scale, leading to a reduction in the price of hydrogen from the baseline of 8.5 euro/kg (Figure 2) to 6.5 euro/kg by the year 2050. Further details on this are provided in the chapter "Results."

Maintenance cost

According to the U.S. Department of Energy, the maintenance cost of diesel HDTs is expected to be higher than the maintenance cost of hydrogen FC HDTs in the future. FC vehicles typically require less maintenance than vehicles with internal combustion engines. The electric motors that propel electric vehicles have fewer moving parts than gas engines. Having fewer components means they need less maintenance (U.S. Department of Energy, 2022). The maintenance of a diesel HDT is set at 0.19 euro/km and the maintenance of a hydrogen FC HDT is set at 0.14 euro/km (Basma et al., 2023).

Total cost of ownership

The TCO is the fixed cost, the cost of driving, and the maintenance cost. The cost of driving and maintenance costs are variable and depend on the distance covered. It is assumed that HDTs cover an equal annual distance, set to an average of 78,000 kilometers per year (CBS, 2023). The average lifespan of a first-time truck is set at eight years, derived from the current average lifespan of 7.6 years (CBS, 2023). It is assumed that truck owners will replace their trucks after eight years. This thesis disregards any potential proceeds from selling the old truck, assuming that the resale value of both diesel and hydrogen FC HDTs are relatively similar.

There are currently 146,500 trucks in the Netherlands (CBS, 2023). It is assumed that these trucks are evenly distributed in age, ranging from 1 to 8 years old. This implies that a consistent number of older trucks in the current fleet are phased out each year, leading to the complete replacement of the entire current fleet after 8 years. At last, it is assumed that both the annual distance covered and the life expectancy remain consistent and equal for both hydrogen and diesel HDTs.

With the fixed and variable costs and the distance covered by the HDTs, the TCO is calculated. The TCO is the foundation of the subsidy program, as the TCO is covered by the subsidy program. The calculation of the TCO is schematically shown in Figure 3.
Please note that Figure 3 only depicts the detailed costs associated with hydrogen FC HDTs, which are identical to the type of costs incurred by diesel HDTs.

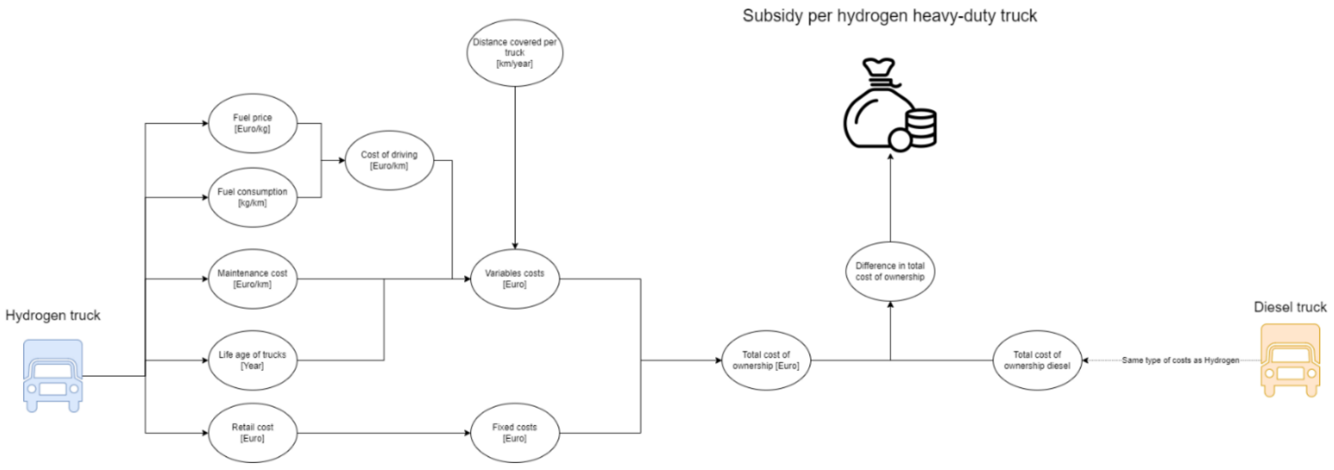

Figure 3: *Schematical overview of the total cost of ownership.*[2]

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[2] *The total cost of ownership are divided into the fixed cost, cost of driving and maintenance cost. These types of costs are for hydrogen fuel cells and diesel heavy-duty trucks the same. The total cost of ownership difference is set to be the subsidy.*

4.1.2 Infrastructure cost

To implement hydrogen FC HDTs in the Netherlands, partly new infrastructure must also be financed. Conventional fossil fuel stations are not capable of fueling hydrogen, therefore hydrogen fueling stations must be installed. The cost of a fueling station is roughly 1.5 million euros, and fuels about 1.500 kg of hydrogen per day (Department of Energy USA, 2021). This results in the capability of refueling between 100 and 120 hydrogen FC HDTs, depending on the engine consumption.

However, researchers warn about potential additional costs to the infrastructure such as reinforcement of pipeline assets and extra maintenance (Lipiäinen, 2023). Given the undefined nature of these costs, the thesis exclusively focuses on the installation expenses of a hydrogen fuel station, disregarding potential additional costs. Nevertheless, it acknowledges these additional expenses by incorporating a "Pro-Memorie" cost within the infrastructure. This implies that the actual infrastructure costs exceed the estimated current cost, thus requiring the NPV to also account for these uncertain expenses.

4.2 Social gains

The subsidy program and infrastructure costs are considered social costs since public funds could be allocated to other activities. Conversely, the social gains refer to the societal benefits of implementing hydrogen FC HDTs in the transport sector. The social gains are divided into two categories: emission reduction and social gain from the perspective of the truck owner.

Emission reduction

The CO_2 emission price varies over time and is categorized into four possible scenarios. Depending on the scenario applied, the reductions may result in greater social benefits (Table 3). The "High" scenario is used in the general CBA guidelines and will therefore also be used in this analysis (PBL, 2013).

Table 3: *CO_2 emission price per scenario in euro/tCO_2 (Handboek milieuprijzen, 2023).*

Year **Scenario**	2021	2030	2050
Low	€ 19	€ 26	€ 52
High	€ 77	€ 104	€ 208
Two-degree exploration Low	€ 100	€ 130	€ 260
Two-degree exploration High	€ 480	€ 650	€ 1.300

NO_x, $PM_{2.5}$, and PM_{10} emissions does not have time dependent emission prices but rather three scenarios; low, central and high. For this thesis, the emission price of scenario “central” is used, as this scenario is also used by the general CBA guideline (Table 4).

Table 4: *NOx, PM2.5 and PM10 emission price per scenario in euro/tCO$_2$ (Handboek milieuprijzen, 2023).*

Emission	**Low**	**Central**	**High**
NO_x	€ 18,3	€ 29,9	€ 44,1
$PM_{2.5}$	€ 73,3	€ 121	€ 169
PM_{10}	€ 41,4	€ 69,3	€ 97,9

4.2.2 Subsidy gain

The subsidy gain represents a social benefit from the perspective of truck owners, resulting from an increase in consumer surplus. The calculation employs the "rule of half" method, which suggests that as consumer surplus grows, certain truck owners are more likely to transition to a hydrogen truck instead of the null alternative. This inclination arises from the perception that the cost of trucks in the null alternative is excessively high, leading individuals to consider transitioning only with the assistance of a subsidy.

For instance, consider a scenario where a subsidy of 1,000 euros is offered. In this case, some individuals may be motivated to acquire the hydrogen truck even with a minimal subsidy of 1 euro, effectively receiving 1,000 euros in subsidy and resulting in a significant increase in consumer surplus of 999 euros. Conversely, others may only be swayed to make the switch with a larger subsidy, such as 999 euros, still receiving 1,000 euros and leading to a marginal increase in consumer surplus of 1 euro. On average, this leads to a net rise in consumer surplus of 500 euros. This examination, as explained by J.A. Annema (2021), underscores the intricate interplay among subsidies, consumer actions, and the resulting enhancements in consumer surplus.

4.3 Net Present Value

The NPV (NPV) is the difference in the social costs and benefits over the established discount rate. Social costs encompass the expenses related to the subsidy program and additional infrastructure costs in comparison to the null alternative. On the other hand, social benefits consist of the emission reduction with regard to the null alternative and the consumer surplus calculation using the rule of half method. A positive NPV indicates that the social benefits outweigh the social costs, making the subsidy program socially viable. Conversely, if the NPV is negative, it is advisable to allocate resources towards alternative zero-emission initiatives.

5 Null alternative

To assess the social viability of the subsidy program, it is crucial to first define the null alternative. The null alternative represents the scenario without any new rules or regulations. To assess the impact of the subsidy program, all of them will be compared to this null alternative. This chapter commences with an examination of the current rules and regulations governing the heavy-duty transport sector. These regulations provide the framework for constructing a scenario that projects the hydrogen FC HDT implementation in the transport sector in the absence of a subsidy program.

5.1 Regulations

As outlined in the literature review, the European Commission is actively working towards reducing emissions in the transport sector. To achieve this goal, the Commission has introduced the "Regulation on CO_2 emission standards for heavy-duty vehicles" (European Commission, 2023). This regulation mandates a future reduction in the CO_2 emissions of new vehicles. The reduction targets are established as a percentage decrease in CO_2 emissions per kilometer for newly acquired trucks, compared to the CO_2 emissions recorded for trucks in 2019 (Figure 4). This year, new targets have been set to furthermore reduce CO_2 emissions of the truck. The Netherlands is also obligated to work within these targets and will therefore use the same European targets.

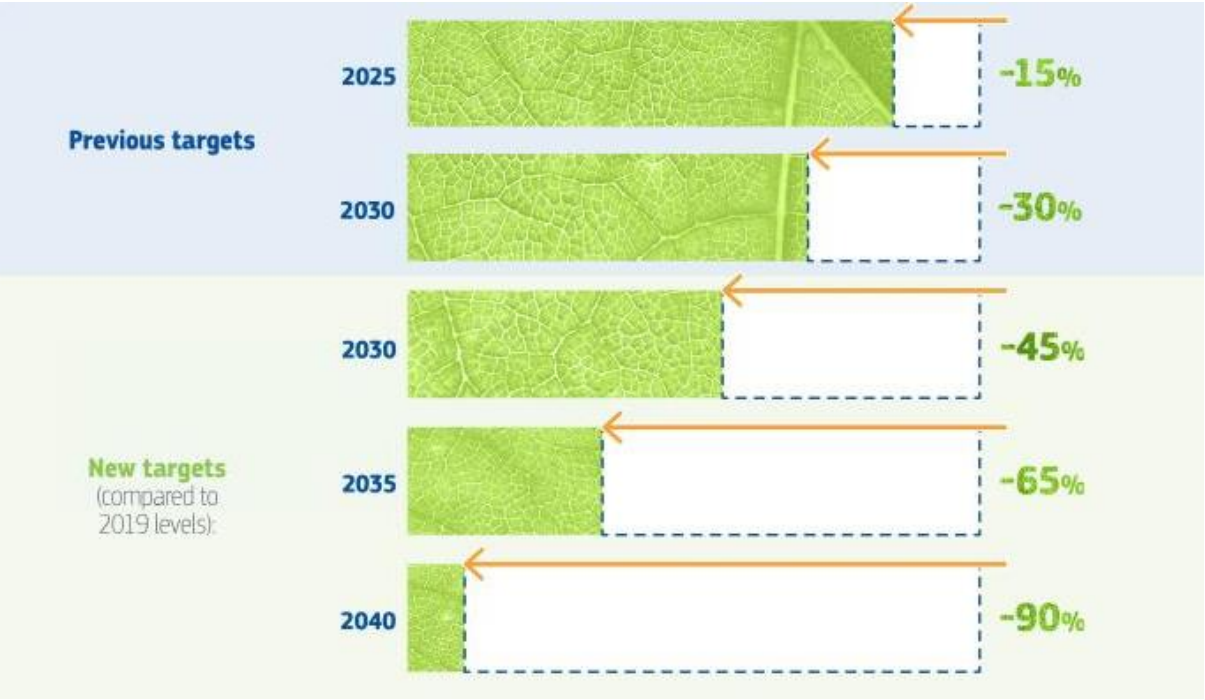

Figure 4: *Emission reduction per truck target relative to 2019 emission per truck (European Commission, 2023).*

It is worth noting that these targets are based on the sum of the trucks sold. For instance, if a truck manufacturer sells in 2040 90 zero-emission HDTs and 10 diesel HDTs from 2019, the overall targets are still met. If these targets are not met, truck manufacturers face substantial fines exceeding the anticipated costs of a zero-emission HDTs. Hence, for this analysis, it is assumed that truck owners will opt to purchase a hydrogen FC HDT rather than risk incurring penalties for non-compliance. As discussed in the literature review, electric HDTs are considered the most cost-effective zero-emission option for short distances but encounter challenges on longer routes. Consequently, in this analysis, hydrogen FC HDTs are anticipated to not dominate the entire HDT market but rather focus on the long-haul transport sector. Given the uncertainty surrounding the cost-effective range of electric trucks, this thesis presents two null alternatives.

In one null alternative, hydrogen FC HDTs are presumed to handle trips exceeding 50 kilometers, while in the other, they tackle journeys surpassing 150 kilometers. CBS data indicates that around 40% of a truck's yearly trips lie within the 0-50 kilometer range, with approximately 75% falling within 0-150 kilometers. Consequently, the "50 km+ scenario" assigns a potential 60% market share to hydrogen, while the "150+ km scenario" allocates a potential 25% market share (CBS, 2020).

In this analysis, it is assumed that the share of electric HDTs remains consistent between both the null and policy alternatives and that this share remains constant over time. This implies that electric HDTs will not experience any technological advancements enabling them to cover longer distances; instead, they will continue to focus solely on short trips. With this consistent market share across both the null and policy alternatives, the costs and social gains remain unchanged and therefore not included in the CBA.

For this analysis, the total number of registered HDTs is sourced from CBS (2023), which, as of 2023, was roughly 146,500 trucks. This results in a potential market share for hydrogen FC HDTs to be either 88.000 HDTs (+50km scenario) or 37.000 HDTs (150+ km scenario). The distribution with potential market share for the 50km+ scenario is schematically shown in Figure 5.

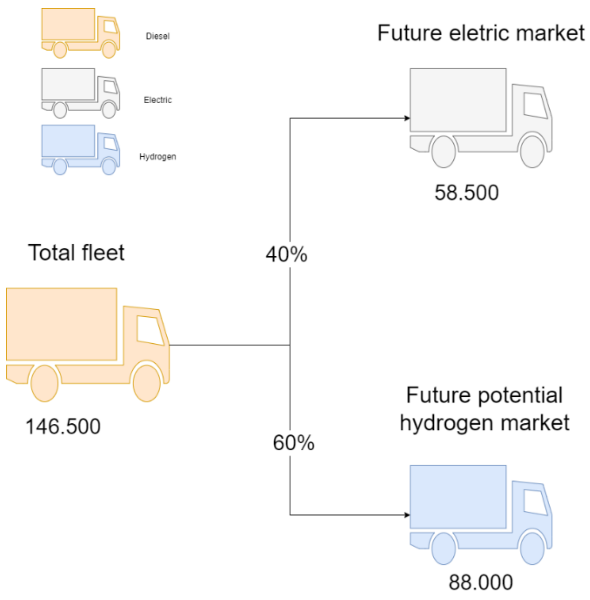

Figure 5: *Potential market share of hydrogen fuel cell heavy-duty trucks in +50km scenario.*

Null alternative

Given that non-diesel HDTs constitute less than 1% of the total fleet in 2022, this thesis assumed a diesel share of 100% in 2023 for this analysis (CBS, 2022). As this thesis uses two null alternatives with varying truck quantities in the potential hydrogen market, it suggests that fewer trucks are required in the 150+km scenario to increase the hydrogen market share compared to the 50+km scenario. This assumption accounts for differing economies of scale across scenarios, ensuring a range of outcomes for a more comprehensive analysis. By exploring two scenarios with different truck quantities per economies of scale, this approach enhances the understanding of price development uncertainties.

The number of registered trucks has increased over the years. For this analysis, the average increase in the registration of trucks from 2015 to 2022 was calculated and is 1.06% (CBS, 2022). As mentioned before, the life age of the truck is set to be eight years, where the age of the truck is equally distributed. This causes the trucks from the current fleet to phase out equally over the eight years (Figure 6).

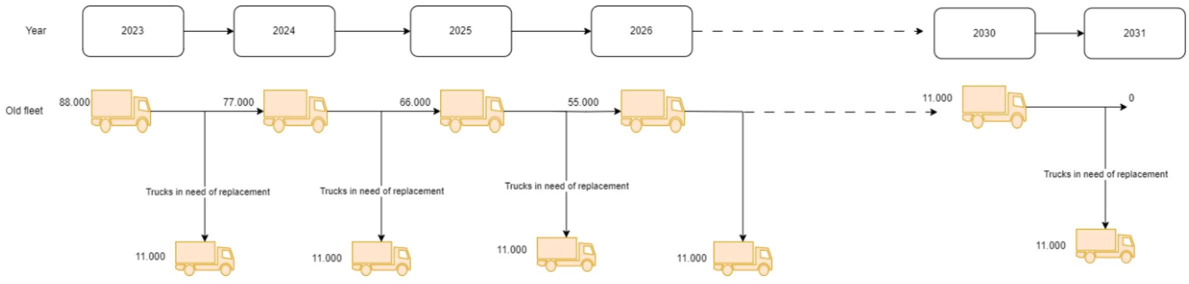

Figure 6: *Schematical overview of the phasing out of the current diesel fleet.*

Starting from the year 2025, the first European targets are set, creating the need to reduce the CO_2 emission per HDT from that year. After that, each year the targets are becoming stricter, resulting in the need to reduce emissions further (Figure 7). However, in 2025, the target presented in Figure 7 does not equate to a 15% reduction from the emissions recorded in 2019, which is equal to an average of 692 grams CO_2 per kilometer per truck (PBL, 2023).
This discrepancy arises because electric HDTs are also assumed to transition, thereby contributing to the overall reduction in emissions. The formula for the target in 2025, for the 50km+ electric share is as follows:

$$CO2\ emission\ 2025 = CO2\ emission\ of\ 2019\ truck * 85\% + CO2\ emission\ target\ 2025 * 40\%$$

This formula indicates that the targets are less strict with a larger share of electric trucks. As electric HDTs are projected to be cost-effective, truck owners will be more likely to first purchase electric HDTs and to only purchase hydrogen FC HDTs if it is necessary.

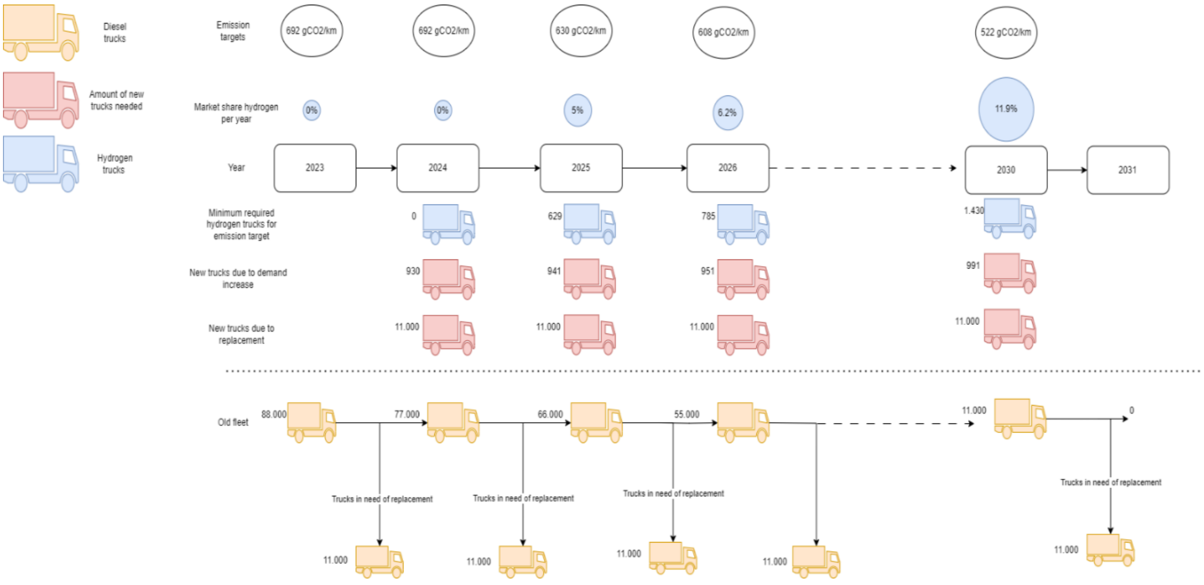

Figure 7: *Schematical overview of the truck development for the null alternative.*[3]

At last, interviews with RVO and the Ministry of Infrastructure and Water Management revealed an ongoing discussion regarding the initiation of a €200 million subsidy for hydrogen FC HDTs and the establishment of hydrogen refueling stations. Since the subsidy budget is still under consideration and no allocation has been finalized, it has not been included in the null alternative analyzed in this thesis. However, the subsequent chapter will explore the implications of this €200 million subsidy and evaluate its potential implementation.

5.2 Result of the null alternative

The null alternative represents the projected outcome in the absence of a subsidy program. Figure 8 illustrates the fleet share development for both null alternatives. The results suggest a slower adoption rate of hydrogen FC HDTs in the 150km+ alternative compared to the 50km+ alternative, primarily due to the higher share of electric HDTs. This delay occurs because FC HDTs are deemed necessary only when emission targets become very strict, starting from the year 2035. In 2040, the final European target of a 90% decrease is established. Beyond this point, the market share of hydrogen is projected to increase at a linear rate of 2.5%. This assumption is founded on the anticipated behavior of car manufacturers, gradually transitioning toward hydrogen rather than reverting to diesel. Finally, Figure 8 illustrates that the goal of achieving emission-free status by 2050 remains unmet. This underscores the necessity for additional policy interventions aimed at further reducing emissions.

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[3] F*igure 7 illustrates the progression of heavy-duty trucks in the model under the null alternative. Each year, new heavy-duty trucks are introduced to meet increasing demand or replace aging vehicles. Moreover, older trucks are phased out every eight years.*

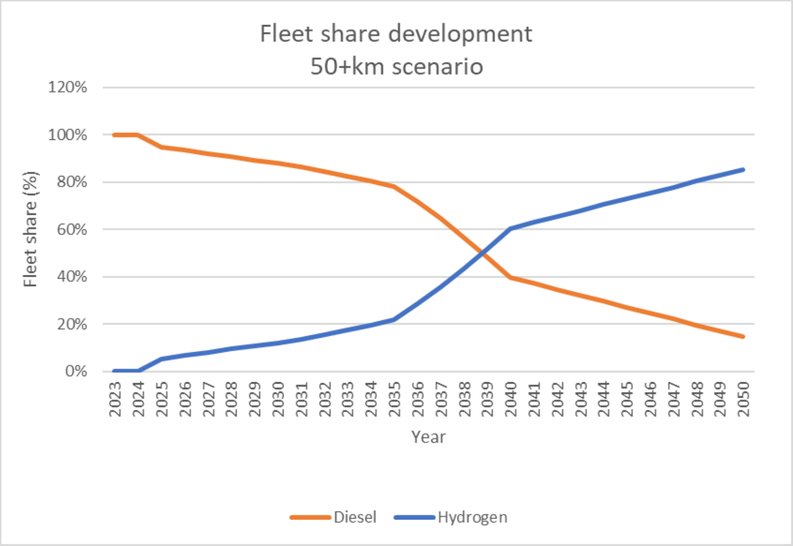

Figure 8.1: *Development of the fleet in percentage for the 50+km scenario null alternative.*

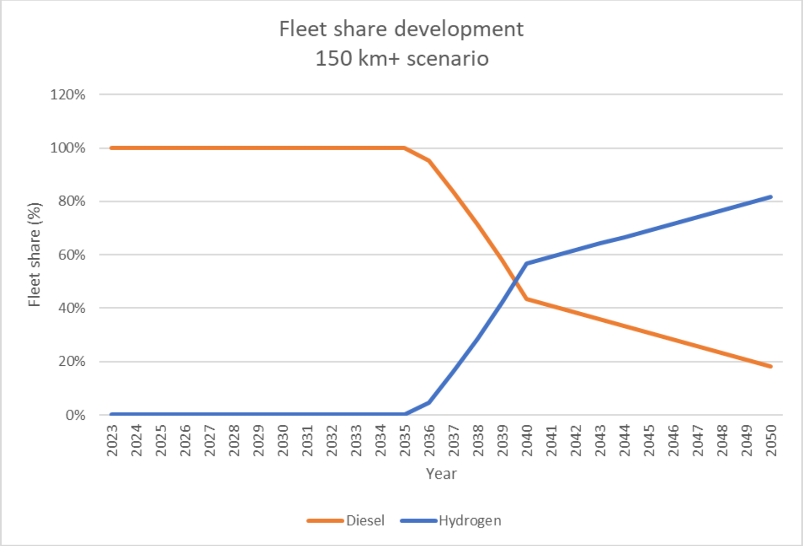

Figure 8.2: *Development of the fleet in percentage for the 150+km scenario null alternative.*

Given that the market share of hydrogen is assumed to form the basis for economies of scale, Figure 8 also provides insight into the development of the fixed costs of hydrogen FC HDTs. This is complemented by Table 4, which shows the different economies of scale and the corresponding years when these economies change, thereby influencing fixed costs, across both scenarios.

Table 5: *Economies of scale for null alternatives.*[4]

Economies of scale Variable	Research and Development	Industrial scale up	Sustainable growth	Full industrialisation
Market share	0%	5%	20%	40%
Fixed cost per hydrogen heavy-duty truck	€ 534,000	€346,000	€ 220,000	€ 179,000
Year of implementation for the 50km+ scenario	2023	2025	2035	2038
Year of implementation for the 150km+ scenario	2023	2036	2038	2039

As a consequence of this delayed integration of hydrogen within the transport sector, the fixed costs persist at relatively high levels for an extended duration. The next paragraph will delve into a detailed examination of the TCO for both diesel HDTs and hydrogen FC HDTs.

5.3 Total cost of ownership

As explained in the chapter “Effects”, the TCO is divided into three categories: fixed costs, costs of driving, and maintenance costs. In Figure 9, the TCO is shown in four years, to indicate the TCO development of hydrogen FC HDTs. Figure 9 illustrates a significant difference in TCO, particularly evident in the early stages, primarily due to the large fixed costs associated with hydrogen FC HDTs. Furthermore, the 150+km scenario shows a higher TCO in 2030, as the economies of scale have not yet decreased the fixed costs. Despite advancements, in the null alternative, the TCO for hydrogen still exceeds that of diesel, highlighting the need for financial incentives to encourage truck owners to transition to hydrogen.

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[4] *This table represent in which year the economies of scale are accelerated with its corresponding fixed cost for the 50+km scenario and the 150+km scenario.*

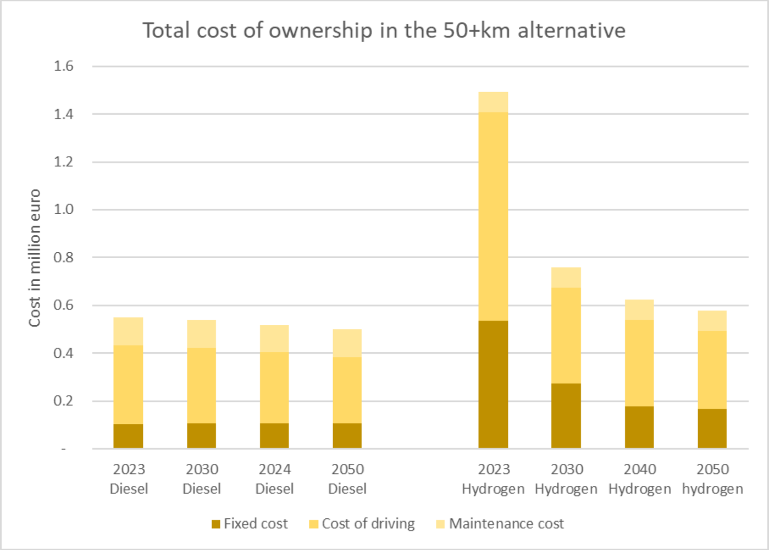

Figure 9.1: *Total cost of ownership of diesel and hydrogen (fuel cell) heavy-duty trucks in the 50+km scenario in 2023, 2030, 2040 & 2050.*

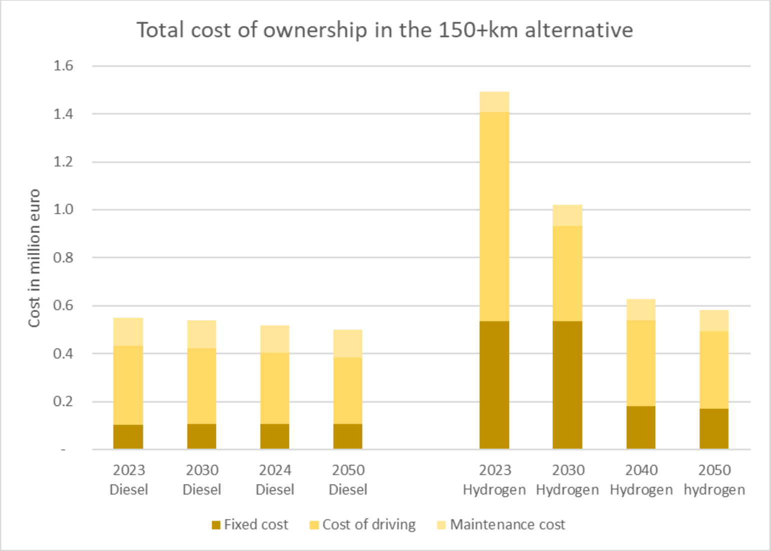

Figure 9.2: *Total cost of ownership of diesel and hydrogen (fuel cell) heavy-duty trucks in the 150+km scenario in 2023, 2030, 2040 & 2050.*

It is interesting to note that despite anticipated future increases in diesel fuel prices (as discussed in the "Effects" chapter), the driving costs are forecasted to decrease. This suggests that the projected efficiency improvements for diesel trucks outweigh the expected rise in diesel fuel prices. This analysis uses the average nominal price increase. It is therefore worth considering that in the future, to incentivize zero-emission driving, European taxes on diesel prices may increase, potentially raising the TCO for diesel HDTs. The two other costs for diesel HDTs remain the same, making the projected TCO stable and relatively robust.

It is interesting to note that despite anticipated future increases in diesel fuel prices (as discussed in the "Effects" chapter), the driving costs are forecasted to decrease. This suggests that the projected efficiency improvements for diesel HDTs outweigh the expected rise in diesel fuel prices. This analysis uses the average nominal price increase. It is therefore worth considering that in the future, to incentivize zero-emission driving, European taxes on diesel prices may increase, potentially raising the TCO for diesel HDTs. The two other costs for diesel HDTs remain the same, making the projected TCO stable and relatively robust.

In summary, the European Commission has implemented targets for the transport sector to reduce the emission of HDTs. These targets have been implemented to project the future of the transport sector. As electric trucks are expected to dominate the short trips, does hydrogen focus on the long-haul routes. This thesis adopted two null alternatives to create a range of possible outcomes. The TCO is especially at the beginning high for hydrogen FC HDTs, as the economies of scale have not yet decreased the fixed costs. Especially for the 150+km scenario, the TCO difference was significant for a long number of years.

In the null alternative, hydrogen remains to have a higher TCO in 2050, making a complete transition not possible, and therefore the objective of an emission-free 2050 is not accomplished. To achieve cost competitiveness for hydrogen FC HDTs in the future, reductions in fixed costs and green hydrogen fuel prices are essential. A subsidy could cover the TCO and facilitate a complete transition of truck owners to hydrogen. Additionally, implementing a subsidy program could accelerate economies of scale, potentially enhancing the economic competitiveness of hydrogen compared to diesel HDTs. In the next chapter, the subsidy program will be explored with the results of the CBA.

6 Results

This chapter shows the results of the Social-Cost Benefit Analysis and therefore evaluates the social viability of the subsidy programs. As discussed in the chapter “Effects”, the subsidy program is set to cover the TCO difference between hydrogen FC and diesel HDTs. Appendix A presents a comprehensive list of all variables used in this CBA, complete with their respective values and sources. Appendix B presents a collection of figures and tables illustrating the evolution of total ownership costs for hydrogen FC HDTs, the yearly budget demands for subsidies, the annual reductions in CO_2 emissions, and the corresponding cash flow for each subsidy program.

6.1 Social Cost-Benefit Analysis result

This CBA proposes three subsidy programs, different in the year of implementation. This analysis assumes that the TCO difference between hydrogen FC and diesel HDTs is covered from the start of the subsidy. After the start year of the subsidy, each year the economies of scale will be accelerated matching the market share of hydrogen in that economies of scale (Table 2). After full industrialization, the market share is set at 100%, meaning that all newly purchased HDTs will be hydrogen FC HDTs.

Table 6 displays the subsidy implementation year alongside the necessary subsidy budget to offset the disparity in the TCO. Additionally, it provides the corresponding CO_2 emission reduction associated with each subsidy program. The analysis considers three different starting dates to provide comprehensive guidance to policymakers in the decision-making process. Each starting date corresponds to distinct economies of scale dynamics: initiating the subsidy later aligns more closely with the economies of scale observed in the null alternative, while an earlier start is assumed to accelerate economies of scale.

Table 6 : *Budget requirements (Bn euro) in and CO_2 emission (Mton CO_2) reduction for early, middle & late subsidy.*

Subsidy	**Year of implementaion**	**Subsidy budget 50+km scenario (Bn euro)**	**Subsidy budget 150+km scenario (Bn euro)**	**CO_2 emission reduction 50+km scenario (Mton CO_2)**	**CO_2 emission reduction 150+km scenario (Mton CO_2)**
Early	2024	13,4	4,2	47,9	23,5
Middle	2034	10,2	2	15,4	6,5
Late	2040	8,9	0,8	6,7	3,1

Table 6 shows that if policymakers wish to have the highest emission reduction, the early subsidy is the best option. However, this subsidy also requires the highest subsidy budget. The proposed subsidy budget of 200 million euros is exceeded in all subsidy programs. To achieve a complete transition to hydrogen long-haul FC HDTs, policymakers may need to consider increasing the subsidy budget, as will be discussed further in the chapter "Recommendations".

The result of the CBA is based on the social costs and benefits of the policy alternative in relation to the null alternative. First, the different effects are again shown to better understand the results in Table 7. As outlined in the "Effects" chapter, the social costs consist of the subsidy and the expenses related to infrastructure, which include the installation of hydrogen fuel stations. However, certain additional expenses, such as pipeline reinforcement and maintenance costs, have not been accounted for as the details are currently unavailable. Therefore, the infrastructure costs include a "Pro-Memorie" provision, indicating that uncertain additional expenses are expected to increase the infrastructure costs.

The social effects consist of the increase of consumer surplus, calculated with the rule of half method, and the emission reduction in relation to the null alternative. There are four types of emission reduction: CO_2, NO_x, $PM_{2.5}$ and PM_{10}. These emission reductions are multiplied by their respective emission prices to standardize the unit type for all variables into euros.

Finally, the NPV can be derived from the known social costs and benefits. The NPV serves as a metric for the social cost-benefit ratio, determining the social viability of the alternative. A negative NPV indicates that the social costs exceed the social benefits, rendering the alternative socially undesirable and thus should not be implemented. It is important to note that due to additional unknown infrastructural expenses, the actual NPV is expected to be slightly lower than the presented NPV in Table 7.

Table 7: *Result of the Social Cost-Benefit Analysis.*[5]

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-12.4	-4.1	-11.9	-2.3	-10.3	-1.2
Infrastructure	-1.1 – PM	-0.9 – PM	-0.5 – PM	-0.2 – PM	-0.3 – PM	-0.1 – PM
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	6.2	2.0	5.9	1.1	5.2	0.6
CO_2 reduction	4.6	2.3	1.6	0.7	0.7	0.3
NO_x reduction	2.7	1.3	1.0	0.4	0.4	0.2
$PM_{2.5}$ reduction	0.7	0.3	0.2	0.1	0.1	0.1
PM_{10} reduction	1.7	0.8	0.6	0.3	0.3	0.1
Net Present value	**2.4 – PM**	**1.8 - PM**	**-3.1 - PM**	**0.1 - PM**	**-3.9 - PM**	**0 - PM**

Table 7 presents the outcome of the CBA, where the first row shows the different alternatives, relative to the two null alternatives. The values are standardized to billion euros, whereas the social costs are divided into the subsidy and the infrastructure costs, and the benefits are the increase of consumer surplus and the emission reduction. At the bottom of the table, is the NPV of each alternative, where a positive NPV indicates that the alternative is considered socially viable. It is important to keep in mind that additional infrastructure costs are not incorporated in this analysis.

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[5] *This table represent in which year the economies of scale are accelerated with its corresponding fixed cost for the 50+km scenario and the 150+km scenario.*

As already mentioned in this chapter, the subsidy is the highest at an early subsidy. This is particularly notable in the 50+ km scenario, where a larger number of hydrogen FC HDTs require subsidization compared to the 150+ km scenario, where electric HDTs are presumed to hold a dominant market share. It is also worth noting that the proposed allocation of 200 million euros, with one-third of the budget for infrastructure and two-thirds for covering the TCO of hydrogen FC HDTs, does not align with the distribution indicated by this analysis. Even considering the additional infrastructure expenses, it is unlikely that infrastructure costs will constitute one-third of the total social cost.

The increase in consumer surplus represents the first social benefit and is calculated using the rule of half method. Consequently, the consumer surplus for each alternative equals half of the subsidy from the social cost. Hence, this social gain is highest when high subsidy budgets are required.

Finally, the social gains from emission reduction are presented. It is observed that CO_2 reduction yields the highest social gain compared to other types of emission reduction. Despite $PM_{2.5}$ and PM_{10} having the highest emission prices (Table 4), they result in significantly lower social gains. This disparity could be attributed to diesel exhaust effectively filtering a large portion of these emissions, resulting in relatively low emissions in the null alternative. This outcome underscores the importance of producing hydrogen from renewable sources, as utilizing natural gas for hydrogen production leads to substantial CO_2 emissions, which would probably result in negative NPV values for all scenarios. Now, the results of each subsidy program will be further explored.

Early subsidy

The early subsidy results in a positive NPV for both alternatives, making it a socially viable outcome. The NPV of 2.4 and 1.8 billion euros, respectively, is likely to remain positive with the additional infrastructural expenses. As the infrastructural expenses are now 1.1 and 0.9, the additional expenses must be the same value as the installment of the hydrogen fuel stations which is unlikely. Comparing the two scenarios shows few changes in NPV, choosing the best scenario is not possible. To determine the best market share of hydrogen FC HDTs, it is from the perspective of the policymakers to determine what effect they find most valuable. If policymakers have a stricter budget, the 150+ km scenario is best suited, as it requires much less subsidy budget requirements. If there is no budget requirement whatsoever, the 50+km scenario is best suited as this results in the highest emission reductions and social gains. When looking at the internal rate of investment (IRR), the 50+km scenario has an IRR of 5%, while the 150+km scenario holds 9,1%. Therefore, relatively the 150+km scenario is considered the best outcome.

Policymakers should therefore perhaps only focus on the trips exceeding 150 kilometers to switch to hydrogen, rather than implementing hydrogen on a larger scale. Finally, in the early subsidy alternative, hydrogen FC HDTs become cost-competitive with diesel by the year 2048. This shift is due to the accelerated economies of scale, leading to reduced fixed costs, and an anticipated decrease in hydrogen fuel prices driven by increased demand. These factors combined make hydrogen FC HDTs a financially viable option. Consequently, the subsidy would cease from that point onward, as hydrogen FC HDTs would be sufficiently mature to operate without government support. However, it is important to note that these assumptions regarding economies of scale and hydrogen fuel price development are speculative. In reality, predicting the price dynamics of fixed costs and fuel prices is inherently uncertain.

Middle subsidy

The results of the middle subsidy show a negative outcome for the 50+km scenario and a slightly positive outcome for the 150+km scenario. In the 50+km scenario, the NPV is -3 billion euros, making it socially non-viable, whereas the NPV for the 150+km scenario is 0.1 billion euros, indicating a positive outcome. However, if the additional infrastructure expenses are reduced, it may cast doubt on the social viability of the 150+km scenario. With an IRR of 2%, the return on investment for the 150+km scenario is minimal. The difference in NPV between the two scenarios can be attributed to the high initial costs in the early years of investment in the 50+km scenario. To accelerate the economies of scale, significant subsidies are required, particularly for the 50+km scenario, given the larger number of trucks needing subsidies. Despite these high initial costs, the emission reductions gradually generate substantial social gains over time, with greater gains as the subsidy program extends. Because the early subsidy starts so soon, the emission reduction generates enough social gain over the years, to compensate for these large initial investments.

Further exploration of this behavior is detailed in Appendix B: Results of the CBA. Additionally, it is noteworthy that in the middle subsidy scenario, the economies of scale do not accelerate fast enough for hydrogen FC HDTs to become cost-competitive with diesel. If policymakers intend to start the subsidy program in 2030 and aim to maintain an emission-free transport sector beyond 2050, an extension of the subsidy program will be necessary. This extension could lead to increased subsidy costs for the program.

Late subsidy

Starting in 2040, the late subsidy enters a hydrogen market already in full industrialization in the null alternative (Table 5). Despite significantly lower social costs compared to other alternatives, the NPV for the 50+km scenario is negative, while for the 150+km scenario, it is zero. Given this, it is probable that the NPV of the 150+km scenario with the additional infrastructure expenses will also be negative.

The negative NPV is due to the emission reduction in relation to the null alternative for the late subsidy is small, creating a small social gain. Additionally, as explained in the previous paragraph, since emission reductions start generating significant social gains a few years after the initial investment, the late subsidy scenario does not allow enough time for these social gains to offset the investment costs. Policymakers are advised against delaying investment in anticipation of price decreases, as the late subsidy lacks the necessary time to become socially viable. Moreover, even the subsidy requirements of the late subsidy exceed the current 200 million subsidy budget plans. The next paragraph will explore the possibilities of implementing such a subsidy program.

6.2 Proposed subsidy exploration

The Dutch government has proposed a 200 million euro subsidy aimed at accelerating the use of hydrogen in the transport sector (Ministry of Infrastructure and Water Management, 2022). This financial support covers both infrastructure development and the acquisition of hydrogen trucks. Following interviews with the Ministry of Infrastructure and Water Management and RVO, it is anticipated that approximately two-thirds of the costs will be allocated to the procurement of trucks, while the remaining one-third will be directed towards infrastructural expenses.

Differently from the previous alternatives, the amount of subsidy being spent is limited. Therefore an early adaptation is not possible as it would greatly exceed the budget. It is better to wait, to reduce the TCO difference leading to more trucks being subsidized. However, waiting till the very last moment does not lead to a viable NPV as the first years of investment cause a negative cash flow. Also, the early subsidy showed the importance of accelerating the economies of scale, to reduce the TCO difference between hydrogen and diesel trucks and therefore lower the subsidy needed. For this proposed subsidy, some key years have been analyzed to reduce the economies of scale with the least amount of money spent.

The first conclusion is that the objective of becoming emission-free in the year 2050 is not possible. This is due to the limited years of subsidizing, where a hydrogen truck was not able to become economically viable compared to diesel trucks. If the subsidy was only in the year 2050, the NPV would be negative for both alternatives, as the investment costs would outweigh the relatively small emission reduction in the year 2050.

For the 50km+ scenario, it was not possible to create a positive NPV. Due to the large amount of trucks, the subsidy budget was quickly depleted making it only possible to accelerate the economies of scale once. Only in the year 2033, with a subsidy of 110.000 euros on the retail of the truck, it was possible to quicken the economies of scale from an industrial scale up to sustainable growth. In the null alternative, this economy of scale was realized in the year 2035 for the 50km+ alternative. This was by accelerating the market share from 17% to 20% which costs roughly 200 million euro.

For the 150km+ scenario, fewer trucks need subsidy making it possible to subsize for multiple years. Again, for this scenario, the subsidy was used to accelerate the economies of scale in specific years to reduce the costs of hydrogen trucks in combination with an emission reduction. In the 150km+ scenario, it was possible to subsidize for three years therefore accelerating the economies of scale three times.

The subsidy starts in the year 2035 to accelerate the research and development phase with one year. The subsidy is again in the years 2036 and 2038 to further accelerate the economies of scale. The total subsidy is 120 million euros making it within the budget of 200 million. With the additional 80 million euros, it is possible to purchase over 50 hydrogen fueling stations. This alternative should subsidize roughly 2.000 hydrogen trucks, which is well within the boundaries of a hydrogen fueling station. The results of the CBA are shown in Table 8.

Table 8 : *Result of the proposed subsidy budget.*

Alternatives	**200M subsidy**	
Scenario **Effects**	**50km+**	**150km+**
Costs	Bln euro	Bln euro
Subsidy	0.26	0.1
Infrastructure	0.02 – PM	0.02 – PM
Social effects	Bln euro	Bln euro
Subsidy gain truck owners	0.13	0.06
CO_2 reduction	0.01	0.07
NO_x reduction	0.01	0.04
$PM_{2.5}$ reduction	0.002	0.01
PM_{10} reduction	0.004	0.02
Net Present value	**-0.1 - PM**	**0.1 - PM**

The results reveal that achieving a positive outcome for the 50+km scenario is unfeasible due to the substantial subsidy required to accelerate economies of scale. Because the subsidy opportunity is limited, the resulting emission reduction remains relatively small compared to the null alternative. Conversely, a positive outcome was attainable for the 150+ km scenario. However, this thesis wishes to acknowledge that the approach of strategically selecting years to stimulate economies of scale may not be feasible in reality. Predicting when economies of scale will accelerate and pinpointing specific years for acceleration is considered impractical. Policymakers should reconsider their proposed subsidy budget, as implementing it in a socially viable manner seems not possible. If policymakers intend to scale up the adoption of hydrogen FC HDTs, an increase in subsidy is necessary. Further details on this matter can be found in the "Recommendations" chapter.

In conclusion, starting the subsidy program requires the highest subsidy budget but also generates the largest emission reduction relative to the null alternative. Looking at the results of the CBA, it can be concluded that starting the subsidy as soon as possible is the best method of implementing a socially viable subsidy program.

The early subsidy 150+km scenario resulted in the highest IRR, this is because the initial investment costs are the highest to accelerate the economies of scale. For the 150+km scenario, fewer trucks have to be subsidized to reduce these fixed costs, highlighting the complexity of working with an assumed economy of scale development.

The subsidy budget proposed by the Dutch government is however not nearly enough to cover such a subsidy program. With a proposed 200 million euro subsidy, it is not possible to accelerate the hydrogen FC HDT sector to an emission-free 2050. Therefore, this thesis wishes to address the need for policymakers to rethink their proposed subsidy budget, as it is unlikely that this subsidy will generate a socially viable outcome.

In projecting the future of hydrogen FC HDTs, this thesis relies on a multitude of assumptions drawn from research papers and interviews. However, these assumptions were often based on a range of variables or other uncertain developments. Recognizing the need for a more comprehensive exploration of these uncertainties, this thesis acknowledges the importance of conducting a sensitivity analysis and subsequent scenario analysis in the following chapters to enhance the robustness of the outcome and better inform policymakers.

7 Sensitivity analysis

In this chapter, a sensitivity analysis is conducted to identify key input variables that significantly influence the outcomes. Sensitivity analysis serves as a critical tool in research and decision-making processes, allowing for the systematic exploration of how variations in input variables impact model outcomes. By identifying influential variables, researchers can gain valuable insights into the robustness of their analyses and better inform decision-making processes.

Furthermore, given that the model outcome relies on a set of assumptions typically derived from a range of expected variables, these key input variables will be used in the next chapter for a scenario analysis. This exploration will involve assigning different values to the key input variables, providing policymakers with a more comprehensive understanding of potential risks and opportunities.

The sensitivity analysis involves independently adjusting each variable by both +5% and -5% of its original value and recalculating the NPV. The difference between the recalculated NPV and the original NPV obtained from the initial CBA serves as a measure of the influence of each variable on the model's outcome. The variables with the most influence on the outcome of the model will be used in the scenario analysis. In Appendix C, the table presents the results of each variable with the ±5% adjustments, along with the corresponding percentage difference in NPV.

The result of the sensitivity analysis showed that the following five variables have the most influence on the NPV: fuel price of diesel, fuel price of hydrogen, fuel consumption of diesel, fuel consumption of hydrogen, and fixed cost of hydrogen FC HDTs. Due to the extensive number of scenarios that would result from incorporating all five variables, a reduction is deemed necessary. Since fuel price and fuel consumption both influence the cost of driving, only the fuel prices of hydrogen and diesel are considered for the scenario analysis. This decision is based on the assumption that engine consumption is a more reliable predictor than the fluctuating prices of diesel and hydrogen fuel in recent years. Furthermore, an additional reduction involves consolidating the hydrogen fixed costs and hydrogen fuel price into a single hydrogen variable. In this setup, a high hydrogen variable corresponds to both high hydrogen fixed costs and high hydrogen fuel prices. The other variable would then be diesel fuel price.

8 Scenario analysis

The scenario analysis uses two variables, each with high and low values, resulting in a total of four scenarios. The first variable is the diesel price, which can be adjusted through taxation by the Dutch government, reflecting the level of environmental awareness. High environmental awareness implies an increase in diesel fuel prices, and vice versa. The second variable is the hydrogen price, encompassing both fixed costs and fuel prices. This creates four planes; these planes correspond to the four scenarios that will be discussed in this chapter (Figure 10). Details of the high and low values for these variables are provided in Appendix D, along with the sources and values used for each.

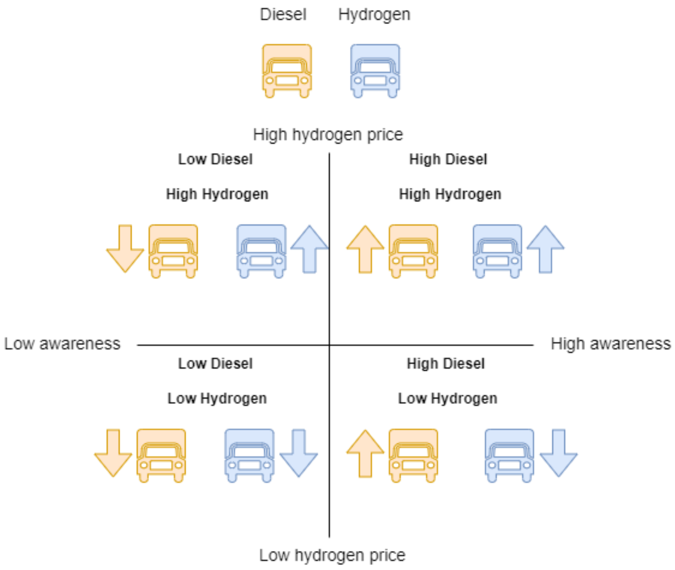

Figure 10: *Schematical overview of the four scenarios.*[6]

After evaluating the four scenarios, an additional analysis focusing on the CO_2 emission price will be performed. This analysis addresses the ongoing political debate in the Netherlands concerning the appropriate CO_2 pricing for CBA.

In this chapter, only the CBA results of the three policy alternatives; early, middle, and late subsidy will be presented. The calculations remain the same, where the subsidy will cover the TCO difference of hydrogen and diesel trucks. The 200 million budget policy alternative is not in the scenario analysis due to a limited time, as the 200 million budget needs intensive modeling to find the best solution.

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[6] *This table represent in which year the economies of scale are accelerated with its corresponding fixed cost for the 50+km scenario and the 150+km scenario*.

8.1 Low diesel, High hydrogen

In this scenario, diesel fuel is set at a low value while hydrogen values are set at high levels, depicting a worst-case scenario for hydrogen. Here, hydrogen price developments lag behind, keeping costs elevated, while the diesel price is lowered due to minimal environmental awareness.

Table 9: *Result of the scenario analysis with low diesel fuel price and high hydrogen prices.*

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-96.3	-25.7	-65.4	-10.7	-44.4	-5.8
Infrastructure	-1.3 – PM	-1.0 - PM	-0.6 - PM	-0.2 - PM	-0.3 - PM	-0.2 – PM
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	48.2	12.8	32.7	5.4	22.2	2.9
CO_2 reduction	4.6	2.3	1.6	0.7	0.7	0.3
NO_x reduction	2.7	1.3	1.0	0.4	0.4	0.2
$PM_{2.5}$ reduction	0.7	0.3	0.2	0.1	0.1	0.1
PM_{10} reduction	1.7	0.8	0.6	0.3	0.3	0.1
Net Present value	**-39.7 – PM**	**-9.2- PM**	**-29.9 – PM**	**-4.0 – PM**	**-21.0 – PM**	**-2.4 - PM**

Table 9 reveals negative NPV across all alternatives, notably with significantly higher subsidy requirements than the analysis using average values. Unlike the results from average values, the earliest subsidy program yields the most negative outcome As social costs consistently outweigh social benefits annually, extending the model's duration leads to an increasingly negative cash flow each year, consequently resulting in a more negative NPV. Policymakers need to recognize that in a worst-case scenario, the subsidy requirements would be high, with no prospect of achieving a socially viable outcome.

8.2 Low diesel, Low hydrogen

In this scenario, both hydrogen and diesel are set at their low value, suggesting a scenario characterized by low environmental awareness but with a strong economy capable of driving a successful breakthrough in hydrogen price.

Table 10: *Result of the scenario analysis with low diesel fuel price and low hydrogen prices.*

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-10.3	-3.8	-2.1	-0.5	0.0	0.0
Infrastructure	-1.0 – PM	-0.8 – PM	-0.4 – PM	-0.2 - PM	0.0	0.0
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	5.2	1.9	1.0	0.2	0.0	0.0
CO_2 reduction	4.6	2.3	1.6	0.7	0.0	0.0
NO_x reduction	2.7	1.3	1.0	0.4	0.0	0.0
$PM_{2.5}$ reduction	0.7	0.3	0.2	0.1	0.0	0.0
PM_{10} reduction	1.7	0.8	0.6	0.3	0.0	0.0
Net Present value	**3.6 – PM**	**2.0 – PM**	**1.9 – PM**	**0.9- PM**	**0.0**	**0.0**

Table 10 shows a positive NPV for all alternatives expect for the late subsidy, where all effects equals zero. This is because in the null alternative hydrogen becomes cost-competitive in the year 2037 for the 50+km scenario and 2040 for the 150+km scenario. This means that after those years, truck owners are transitioning towards hydrogen without the need for a subsidy, making a subsidy program starting in 2040 not needed. Accelerating the transition with early and middle subsidies remains socially viable, as, despite the program's duration lasting until 2037 or 2040, this brief acceleration ultimately results in more social benefits than social costs. The additional infrastructure costs are likely manageable, as they need to be three to five times greater than the installation expenses of hydrogen fueling stations for the NPV to become negative, an outcome that seems unlikely.

If improvements in the affordability or efficiency of hydrogen fuel cost and fixed cost occur, it could result in cost-competitive hydrogen FC HDTs before 2050. While starting a subsidy program remains socially viable, considering the objective of achieving emissions-free status by 2050, one might question its necessity. Especially as these subsidy programs still exceed the current proposed subsidy budget.

8.3 High diesel, High hydrogen

In this scenario, both variables are set to their high values, indicating a situation where both hydrogen and diesel become expensive. This situation could reflect an attempt to forcefully promote hydrogen adoption, resulting in increased diesel prices in the hopes of stimulating hydrogen usage. However, this strategy proves unsuccessful as hydrogen implementation falls short of expectations.

Table 11: *Result of the scenario analysis with high diesel fuel price and high hydrogen prices.*

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-74.3	-20.6	-44.2	-7.5	-28.5	-3.8
Infrastructure	-1.3	-1.0 – PM	-0.6 – PM	-0.2 – PM	-0.3 – PM	-0.2 - PM
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	37.1	10.3	22.1	3.8	14.3	1.9
CO_2 reduction	4.6	2.3	1.6	0.7	0.7	0.3
NO_x reduction	2.7	1.3	1.0	0.4	0.4	0.2
$PM_{2.5}$ reduction	0.7	0.3	0.2	0.1	0.1	0.1
PM_{10} reduction	1.7	0.8	0.6	0.3	0.3	0.1
Net Present value	**-28.8 – PM**	**-6.6 – PM**	**-19.3 – PM**	**-2.6 – PM**	**-13.1 – PM**	**-1.3 - PM**

In this scenario, all alternatives have a negative NPV. This is because the significant difference in total ownership costs requires a substantial subsidy budget. Even with the early subsidy alternative, economies of scale failed to reduce fixed costs, making a subsidy needed until 2050. This scenario underscores the necessity for hydrogen to align with the average projected values. Without this alignment, regardless of the diesel development, the subsidy program will be expensive without a social return on investment. Policymakers should be cautious about initiating a subsidy program without certainty regarding the economy of scale development, as mere increases in diesel prices are insufficient for transitioning toward hydrogen FC HDTs.

8.4 High diesel, Low hydrogen

In this scenario, diesel values are set high while hydrogen values are set to low, representing the most favorable conditions for hydrogen implementation, with hydrogen being the most affordable and diesel the most expensive.

Table 12: *Result of the scenario analysis with high diesel fuel price and low hydrogen prices.*

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-0.8	-0.3	0	0	0	0
Infrastructure	- 0.5 - PM	- 0.2 - PM	0	0	0	0
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	0.4	0.15	0	0	0	0
CO_2 reduction	1.2	1.6	0	0	0	0
NO_x reduction	0.7	1	0	0	0	0
$PM_{2.5}$ reduction	0.2	0.2	0	0	0	0
PM_{10} reduction	0.5	0.6	0	0	0	0
Net Present value	**1.7 - PM**	**3.1 - PM**	**0**	**0**	**0**	**0**

In this scenario, hydrogen FC HDTs achieve cost competitiveness with diesel by 2030 in the 50+km scenario and by 2036 in the 150+km scenario. Consequently, in the middle and late subsidy scenario, hydrogen FC HDTs secure a 100% market share in the null alternative, making a subsidy program unnecessary. Table 12 demonstrates the relatively high infrastructure costs in comparison to the required subsidy budget, underscoring the relatively small subsidy needed to transition a significant quantity of hydrogen FC HDTs. Additionally, the 150+km scenario presents a higher NPV than the 50+km scenario, a deviation from the usual trend where the 50+km scenario outperforms alternatives with positive NPVs. This difference can be attributed to the subsidy program ending sooner in the 50+km scenario compared to the 150+km scenario, resulting in shorter-lasting social gains relative to the null alternative. At last, even in this scenario, the required subsidy budget still surpasses the budget proposed by the Dutch government. Should policymakers intend to start a subsidy program, regardless of the anticipated scenario, they would need to enhance their budget.

In conclusion, the development of fuel prices and fixed costs is crucial for ensuring the social viability of policy alternatives. Failure of hydrogen fuel prices to meet anticipated levels or insufficient developments in the economies of scale would result in all policy alternatives becoming socially non-viable. Policymakers must recognize this risk, as there is a possibility that even with an increase in diesel, the subsidy program would require significant costs without yielding a positive NPV. Conversely, in scenarios where hydrogen performs better than expected, hydrogen FC HDTs could achieve cost competitiveness before 2050, thereby realizing the objective of achieving an emission-free 2050, even in the null alternative.

8.5 CO_2 emission price

This thesis uses the general CBA guidelines established by the PBL Netherlands Environmental Assessment Agency to establish the CO_2 emission price (Table 13). There is ongoing debate regarding the potential use of "Two-degree exploration low" CO_2 emission prices instead of the "High" scenario. This adjustment would increase the social gains from CO_2 emission reduction, thereby potentially resulting in more positive outcomes for other alternatives.

Table 13: *CO_2 emission price per scenario in euro/tCO_2 (Handboek milieuprijzen, 2023).*

Year **Scenario**	2021	2030	2050
Low	€ 19	€ 26	€ 52
High	€ 77	€ 104	€ 208
Two-degree exploration Low	€ 100	€ 130	€ 260
Two-degree exploration High	€ 480	€ 650	€ 1.300

This paragraph examines the "Two-degree exploration low" and "Two-degree exploration high" scenarios to assess the impact of an increase in CO_2 price on the analysis outcome. By doing so, policymakers can gain a clearer understanding of any potential future implications.

Table 14: *Result of the scenario analysis with "Two-degree exploration low" CO_2 emission price.*

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-12.4	-4.1	-11.9	-2.3	-10.3	-1.2
Infrastructure	-1.1 – PM	-0.9 – PM	-0.5 – PM	-0.2 – PM	-0.3 – PM	-0.1 – PM
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	6.2	2.0	5.9	1.1	5.2	0.6
CO_2 reduction	5.8	2.8	2	0.9	0.9	0.4
NO_x reduction	2.7	1.3	1	0.4	0.4	0.2
$PM_{2.5}$ reduction	0.7	0.3	0.2	0.1	0.1	0.1
PM_{10} reduction	1.7	0.8	0.6	0.3	0.3	0.1
Net Present value	**3.6 - PM**	**2.4 - PM**	-2.7 - PM	0.3 - PM	-3.7 - PM	0.1 - PM

Adjusting only the CO_2 emission price increases the social gain from CO_2 reduction. Consequently, with this adjusted CO_2 price, all scenarios have improved outcomes. However, no significant changes are observed, and the middle and late subsidy for the 50+km scenario continues to yield negative results. As for the middle subsidy, the 150+km scenario NPV becomes positive. However, when considering additional infrastructure expenses, achieving a positive NPV becomes uncertain, and if attained, it would likely yield a low IRR. For policymakers, the adjustment of CO_2 emission prices to a "Two-degree exploration low" has an insignificant impact on the NPV outcome and should therefore not alter any major decision-making.

While the adoption of the "Two-degree exploration high" scenario may not be under active debate, this thesis aims to investigate the potential implications of transitioning to this scenario, providing policymakers with a broader understanding of any future implications. Implementing this scenario would substantially increase the CO_2 emission price (Table 13), and the outcomes associated with adopting the "Two-degree exploration high" scenario are detailed in Table 15.

Table 15: *Result of the scenario analysis with "Two-degree exploration high" CO_2 emission price.*

Alternatives	**Early subsidy**		**Middle subsidy**		**Late subsidy**	
Scenario **Effect**	**50km+**	**150km+**	**50km+**	**150km+**	**50km+**	**150km+**
Social costs	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Subsidy	-12.4	-4.1	-11.9	-2.3	-10.3	-1.2
Infrastructure	-1.1 – PM	-0.9 – PM	-0.5 – PM	-0.2 – PM	-0.3 – PM	-0.1 – PM
Social benefits	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro	Bln Euro
Increase of consumer surplus	6.2	2.0	5.9	1.1	5.2	0.6
CO_2 reduction	28.8	14.1	10.1	4.3	4.5	2.1
NO_x reduction	2.7	1.3	1	0.4	0.4	0.2
$PM_{2.5}$ reduction	0.7	0.3	0.2	0.1	0.1	0.1
PM_{10} reduction	1.7	0.8	0.6	0.3	0.3	0.1
Net Present value	**26.6 - PM**	**13.7 - PM**	**5.4 - PM**	**3.7 - PM**	**-0.1 - PM**	**1.8 - PM**

The sensitivity analysis revealed that the CO_2 emission price has a relatively low influence on the outcome. However, with a substantial increase in the CO_2 emission price, reaching roughly five times the amount of the "High" scenario, the social gains increase significantly. All alternatives experience a substantial increase, making almost all alternatives socially viable. The only exception is the late subsidy 50+km scenario, which exhibits a negative NPV. Should policymakers choose to implement the "Two-degree exploration High" scenario, the subsidy program is likely to be socially viable, regardless of when it is implemented.

In conclusion, the fuel price development and fixed costs of hydrogen FC HDTs are crucial for the subsidy program to be socially viable. If the fuel price and fixed cost do not reach the expected outcome, the NPV is negative, even with high diesel prices. In favourable scenarios, where hydrogen fuel prices and fixed costs have fewer costs than expected, the subsidy programs are socially viable. Not only that, hydrogen FC HDTs become cost-competitive to diesel in the null alternative. This means that even without intervention, the objective of an emission-free long-haul transport sector in the year 2050 will be achieved.

In all scenarios, the subsidy exceeds the budget proposed by the Dutch government. If the Dutch government wishes to use the "Two-degree exploration low" CO_2 emission price, the project outcome remains the same. Only when implementing the "Two-degree exploration high" CO_2 emission price, all subsidy programs become socially viable.

9. Discussion

The discussion chapter serves as a critical reflection on the findings presented in this thesis. It aims to evaluate both the strengths and limitations of the research, providing a comprehensive understanding of the implications of the study. Through a detailed analysis of the methodology, theory, results, and interpretation, this chapter seeks to contextualize the research within the broader scholarly discussion, offering insights into its significance and potential impact.

9.1 Discussion on the results

The knowledge gap this thesis addressed in the Chapter “Literature background” was the lack of including social effects in the evaluation of hydrogen FC HDT adoption. In chapter 4 “Social effects”, the social costs and benefits were explored. Especially the fixed costs of hydrogen FC HDTs were difficult to project due to the uncertainty of the price development. Aminudin (2023) shared this finding and concluded that the uncertain nature of fixed costs associated with hydrogen FC HDTs indicates that cost reductions are anticipated but are contingent upon uncertainties. In contrast with Aminudin’s study, this research used a different approach to project fixed-cost development. Namely, by looking at the economies of scale rather than the projected outcome, this thesis made assumptions on how the economies of scale would develop. This method is something other researchers could also implement, as it changes the dynamic of fixed-cost development. The “Recommendations” chapter will elaborate on this point.

Additionally, in Chapter 4 “Social effects” and Chapter 5 “Null alternative”, the difference in TCO of hydrogen FC HDTs and diesel underscored the need to consider social effects, such as emission reduction, on the viability of hydrogen FC HDT implementation. Solely focusing on financial and technical aspects might portray hydrogen FC HDTs unfavorably, emphasizing the importance of integrating more social factors, as suggested by Joshi (2023), in transport sector decision-making.

Furthermore, to reiterate Aryanpur (2024), it is favorable to start a subsidy program for hydrogen HDTs promptly, as delaying action could result in a carbon lock-in. Similarly, chapter 6 “Results” indicated that initiating the subsidy program at the earliest moment would cause the highest social viability, with NPV of 2.4 and 1.8 billion euros, respectively. However, the findings did not indicate a carbon lock-in as an outcome. This contrast in findings appeared because Aryanpur did not implement European targets but rather focused on the cost-competitive traits of different types of HDT alternatives.

At last, Plötz (2022) highlighted the importance of the future cost developments of hydrogen FC HDTs, where postponing the commencement of mass production for these trucks to reduce the fixed cost could diminish the likelihood. Similarly, the results of Chapter 7“Sensitivity Scenario” and Chapter 8 “Scenario Analysis” highlighted the importance of fixed costs in the social viability of the outcome. Only in scenarios where the economies of scale would reduce the fixed costs, the outcome can become socially viable, again sharing Plötz’s findings.

In sum, this thesis shares rather similar findings to other papers, highlighting the social viability of early adoption. In addition, the main concern of the uncertainty of fixed costs has a significant impact on the outcome of the social viability of a subsidy program. A minor contrast with other studies was the comprehensive overview this thesis provided whereas other articles focused on a specific effect. This specialization is more detailed but lacks the comprehensive understanding of implementing hydrogen FC HDTs.

9.2 Strengths

This thesis adopted a quantitative descriptive approach, aiming for systematic analysis without direct researcher interference. A key strength of this thesis lies in its reliance on a diverse range of variables sourced from published literature and interviews with experts. All variables were listed in Appendix A, to increase the objectivity and transparency of the analysis. Furthermore, all variables were listed in the model, allowing for the adjustment of each variable. Altering a variable could result in an immediate change to the overall outcome of the model. This flexibility ensured that future revisions could easily incorporate updated variable values, thereby refining the analysis and its conclusions. Additionally, this systemic analysis included sensitivity and scenario analyses, which provided a more comprehensive understanding of the risks and opportunities associated with implementing hydrogen HDTs.

Given the uncertainty surrounding hydrogen fuel and retail prices, particularly in the future, this analysis highlighted the potential pitfalls of developments not aligning with expected values. By presenting these risks and opportunities, policymakers could make more informed decisions.

This thesis addressed a research gap in the existing literature by focusing on the often-overlooked social effects in the evaluation of hydrogen implementation within the transportation sector. Hence, this research provided not only a financial perspective, comparing the TCO between hydrogen FCs and diesel HDTs but also explored the potential social benefits and/or risks associated with such a transition. This comprehensive approach resulted in the development of a null alternative, creating the opportunity to compare the various subsidy programs. Through this null alternative, the results of this study provided insights for policymakers into the required costs for transitioning to hydrogen FC HDTs and the resulting emission reductions achievable through subsidy programs. This offered policymakers a valuable indication of the potential for creating a socially viable alternative. Notably, this research underscored the urgency for immediate action, suggesting that delaying implementation could diminish the likelihood of achieving a socially viable outcome. Further insights into this issue will be discussed in the following chapter.

Lastly, it is important to emphasize that this thesis was not only relevant for policymakers but also for researchers in the field. By solely focusing on technical and financial developments, one could not grasp the full picture of hydrogen FC HDTs. It was only when social effects were considered that a complete understanding could be achieved, enabling alternatives to become socially viable. Relying solely on technical and financial aspects made hydrogen FCs appear inferior to diesel HDTs, potentially hindering the transition. This thesis highlighted the importance of incorporating social effects for a comprehensive understanding of hydrogen implementation in the transport sector.

9.3 Limitations

While this thesis has made significant contributions to the understanding of implementing hydrogen FC HDTs in the Netherlands, it is essential to acknowledge its limitations. Identifying and discussing these limitations provides transparency and helps contextualize the findings, ensuring a balanced interpretation of the research outcomes. Moreover, this study’s limitations pave the way for future research recommendations.

Data limitations

The data limitations of this study were two-fold. First, due to the lack of solid data on hydrogen’s infrastructural costs, it relied on projected costs for installing hydrogen fueling stations as infrastructure expenses. In these projections, additional expenditures, such as pipeline reinforcement and maintenance costs, were not included due to insufficient data. Consequently, the model's outcomes might have been less precise, as the actual NPV was likely lower than projected. This impacted not only the NPV but also the IRR, thereby influencing the actual costs and benefits of the analysis. With complete infrastructure cost data, a more accurate projected outcome could have been achieved.

Second, much of the data concerning the price trajectory of hydrogen and diesel was provided within ranges. This thesis relied on average values within these ranges or extrapolated from previous years' growth rates. Due to the inherent uncertainty in these ranges, the accuracy of the model's outcomes was limited.

Assumption limitations

This thesis was based on several assumptions, as the uncertain future developments of hydrogen FC and diesel HDTs made it impossible to project the outcome with full certainty. The first and major assumption this thesis wish to acknowledge regarded the economies of scale. The economies of scale represented the projected fixed-cost development of hydrogen HDTs. This thesis adopted the assumption that if the market share of hydrogen FC HDTs increased, the demand for hydrogen FC HDTs would also increase, resulting in a drop in fixed costs for the consumer. This behavior was highly uncertain, as it was likely to be dependent on many other factors such as technological breakthroughs, international demand, and rising zero-emission alternatives. To truly estimate fixed cost development, it is necessary to further explore these economies of scale, as the sensitivity analysis highlighted the importance of the fixed costs of hydrogen FC HDTs. If the fixed costs accelerated at a faster rate, hydrogen would become a much more viable option. However, the other way around also applied: if hydrogen fixed costs did not decrease, policymakers should find other zero emissions alternatives. The next chapter elaborates on these alternatives.

Secondly, while the assumption of producing green hydrogen, hydrogen generated from renewable sources, was validated by interviews with both RVO and the Ministry of Infrastructure and Water Management, it remains a foundational premise. Particularly in the early subsidy 50+km scenario, the projected demand for hydrogen in the coming years is substantial, raising doubts about whether all hydrogen demand can be met with green hydrogen. The literature review indicated that if hydrogen is not sourced from renewable sources, it leads to high CO_2 emissions, as hydrogen will be produced using the Steam Methane Method, where gas is used to produce hydrogen, resulting in substantial CO_2 emissions (Kothari, 2008). Furthermore, the results of the CBA revealed that CO_2 emission reduction yields the highest social gain among the four emissions (CO_2, NO_x, $PM_{2.5}$, PM_{10}) considered. This underscored the importance of hydrogen production being derived from renewable sources.

Third, this thesis lacks exploration into alternative zero-emission technologies. It assumed that short-distance trips are managed by electric HDTs. However, this assumption considers a static trip distance, while advancements in electric vehicle technology may enable them to cover longer distances in the future, similar to the progress seen in personal electric vehicles. Additionally, other zero-emission alternatives like biofuels might offer greater social viability compared to hydrogen. Thus, as it was beyond the scope of this research, the sole focus on hydrogen poses limitations. Chapter 11 will further elaborate on this issue.

Model limitations

The primary limitation of the model was its time horizon, spanning from 2023 to 2050. This timeframe aligns with the thesis objective of achieving emission-free status by 2050. However, the analysis revealed that with the middle and late subsidy programs, the TCO for hydrogen HDTs remains higher than for diesel. Hence, the projected ending subsidies for hydrogen in 2050, could lead to a decline in hydrogen FC HDT adoption afterward. Moreover, extending subsidy programs beyond 2050 would result in higher costs, potentially impacting the social viability of facilitating widespread adoption of hydrogen FC HDTs in the Netherlands.

Scope limitations

Due to constraints in time and resources, this thesis focuses on the adoption of hydrogen HDTs within the Netherlands. However, successful implementation requires expanding the scope to consider the international context of the long-haul heavy-duty sector. Simply installing hydrogen refueling stations domestically would be insufficient, as most long-haul HDTs travel routes across Europe. Without hydrogen refueling stations outside the Netherlands, hydrogen adaption becomes impractical. Implementing hydrogen HDTs in the Netherlands therefore requires a continental transition toward hydrogen adoption. The exploration of a European implementation of hydrogen FC HDTs is briefly explored in the next chapter.

10. Conclusion

For the Dutch government to reach the Paris Agreement, CO2 emissions across multiple sectors must be reduced. This thesis focused on the transport sector, particularly the long-haul heavy-duty truck (HDT) sector, as this sector faces difficulties transitioning towards an emission-free alternative. One alternative that seems promising is the hydrogen Fuel Cell (FC) HDT. In contrast to electric HDTs, which often lack sufficient range for long distances, a hydrogen FC HDT has ranges comparable to those of current diesel HDTs. While prior research has been conducted on the technical and financial developments of hydrogen HDTs, its social effects have frequently been disregarded. This research gap highlights the need for a thorough exploration of the social effects of implementing hydrogen FC HDTs in the Netherlands. This thesis aims to address this gap by examining both the social costs and benefits of subsidizing hydrogen trucks in the Netherlands, offering a perspective on the potential implications for the transportation sector and Dutch society. The goal of this thesis is to conduct a CBA to evaluate the viability of a subsidy program aimed at transitioning diesel HDTs to hydrogen in the Netherlands. The research question of this MSc thesis is:

What is the social cost-benefit ratio of policies that aim for the widespread adoption of hydrogen fuel cell heavy-duty trucks in the year 2050 in the Netherlands?

To answer the research question effectively, first, the sub-questions will be answered. These sub-questions will be addressed in chronological order and will form the basis for the conclusion and the subsequent future research recommendations (Chapter 11).

SQ1: What are the financial, technical, and social effects of the implementation of hydrogen fuel cell heavy-duty trucks in the Netherlands?

This sub-question focuses on the effects of transitioning from a diesel to a hydrogen HDT. According to insights from interviews with RVO and the Ministry of Infrastructure and Water Management, there is an expectation that hydrogen production will shift towards renewable sources, making hydrogen a viable option for an emission-free 2050. Extensive desk research was conducted using Scopus, Google Scholar, and Google to gather published papers and reports on the Total Cost of Ownership (TCO) comparison between diesel and hydrogen FC HDTs. The findings indicate that diesel is currently considered the more financially viable option. Consequently, the abovementioned sub-question leads to the following conclusion:

Hydrogen fuel cell heavy-duty trucks are expected to use hydrogen produced from renewable sources, making it a viable emission-free alternative. However, although the total cost of ownership of hydrogen fuel cell heavy-duty trucks is expected to decrease, diesel heavy-duty trucks will most likely be a financially advantageous option for truck owners. This means that without a subsidy covering the total cost of ownership difference, truck owners are likely to choose diesel over hydrogen in the future.

SQ2: What is the null alternative of the analysis?

The European Commission has established emission reduction targets for the HDT sector by 2040, aiming to achieve a 90% decrease in emissions per truck compared to 2019 levels. This thesis employs two scenarios to assess the implementation of hydrogen HDTs. One scenario focuses on covering all trips exceeding 50 kilometers, while the other scenario targets trips exceeding 150 kilometers. The remaining share of trips is allocated to electric HDTs, which are considered cost-competitive for shorter ranges. This approach accounts for the uncertainty surrounding the future adoption of electric HDTs, providing policymakers with a more comprehensive range of potential outcomes. The conclusion of the second sub-question is:

Due to the higher cost of ownership of hydrogen fuel cell heavy-duty trucks in regard to conventional diesel, truck owners are not voluntarily switching to hydrogen. The current rules and regulations established by the European Commission are set for a 90% $CO2$ *emission reduction per truck in 2040. Without additional steps, the projected outcome is that the objective of an emission-free 2050 in the long-haul sector is not achieved.*

SQ3: How does the null alternative differ from the policy alternative?

To evaluate the policy alternative, the subsidy programs were compared to the null alternative. This thesis Explored three subsidy programs, that differ in the year of implementation. The subsidy programs are set to cover the TCO difference between diesel and hydrogen HDTs. Furthermore, the study examined the proposed subsidy budget allocated by the Dutch government, amounting to 200 million euros, intended for subsidizing hydrogen HDTs and the associated infrastructure. The conclusion of the third sub-question is:

With a subsidy covering the total cost of ownership difference between hydrogen fuel cell and diesel heavy-duty trucks, an emission-free long-haul transport sector is possible in the year 2050. For the early subsidy starting in 2024, it is possible to make hydrogen cost-competitive with diesel heavy-duty trucks in the year 2048. However, all subsidies greatly exceed the current budget of 200 million euros set by the Dutch government.

SQ4: How can the social effects of implementing a subsidy program for hydrogen fuel cell heavy-duty trucks be valued in the Social Cost-Benefit Analysis?

To evaluate the social cost and benefit ratio, all units must be standardized to calculate the social viability of the subsidy program. For the social costs, divided into infrastructure costs and TCO, the unit is already in euros. The social gains, divided into consumer surplus from the perspective of the truck owner and the emission reduction, are also set in euros. The conclusion of this sub-question is:

All effects can be measured in euros. The subsidy and infrastructure are considered to be a social loss, whereas consumer surplus from the perspective of truck owners and the emission reduction of the policy alternative are considered to be social gains. The consumer surplus is determined by using the rule of half method, equating to half of the subsidy. Emission reduction is computed by multiplying the emission reduction by its corresponding emission price.

By addressing the different sub-questions, the main question can be answered and subsequently presented in this thesis conclusion. The main research question is:

What is the social cost-benefit ratio of policies that aim for the widespread adoption of hydrogen fuel cell heavy-duty trucks in the year 2050 in the Netherlands?

This thesis demonstrated the possibility, under various assumptions, of establishing a socially viable subsidy program. The early subsidy alternative, initiated in 2024, yielded a positive Net Present Value (NPV), indicating a socially viable outcome. The NPVs for both the 50+km and the 150+km scenarios were positive, amounting to 1.2 billion euros and 1.5 billion euros, respectively. This suggested that an early subsidy remained socially viable irrespective of the future market share of hydrogen in long-haul transportation. This subsidy program was not only socially viable, with an assumed decrease of fixed costs due to economies of scale, but also made hydrogen FC HDTs cost-effective by the year 2048. This made it possible to stop the subsidy in 2048 and achieve a mature hydrogen market.

With estimated costs of 12 billion euros for the 50+km scenario and 4 billion euros for the 150+km scenario, the early subsidy program promised a significant reduction in CO2 emissions, totaling over 47 million (50+km) tons and 23 million (150+km) tons, respectively. This subsidy greatly exceeded the proposed subsidy budget of 200 million euros set by the Dutch government.

However, it was important to acknowledge the assumption nature of the depicted variables. As mentioned in the discussion, this thesis collected data from multiple sources, using average or most likely outcomes as values for the input variables. Especially for the assumption of the fixed cost of hydrogen FC HDTs, it was important to acknowledge its uncertainty. The assumption that the fixed costs of hydrogen FC HDTs would decrease in the future with economies of scale was supported by a report from a reputable European collaborative initiative. This initiative involved 13 parties from both the private and public sectors, lending credibility to the assumption despite its inherent uncertainty. This thesis assumed that these economies of scale would be determined by the market share of hydrogen FC HDTs, but the actual behavior of these economies of scale remained uncertain. The sensitivity analysis highlighted the significant impact of fixed costs on the model's outcome, making it a crucial variable. Further exploration of these fixed costs in the scenario analysis revealed that in less favorable scenarios, the early subsidy alternative was no longer socially viable and required a significantly larger subsidy.

Additionally, the lack of comprehensive data excluded a complete financial assessment of infrastructure costs. Consequently, the actual NPV was likely to be lower, as expenses like pipeline reinforcement were not factored into the infrastructure costs. Policymakers should have been mindful of these uncertainties and risks, which were further explored in the forthcoming recommendations. These recommendations would have incorporated the thesis conclusions to provide actionable guidance for policymakers' decision-making processes.

11. Recommendations

The goal of this thesis was to provide policymakers with information on the social viability of a subsidy program aimed at transitioning diesel HDTs to hydrogen in the Netherlands. This study's results indicate that, under several assumptions, it is possible to start a socially viable subsidy program. Such a program offers substantial CO2 emission reductions and makes achieving an emission-free long-haul transport sector by 2050 possible. However, given that this subsidy program would require a considerable allocation from the societal budget, which could otherwise be allocated to various social activities, this thesis recommends delaying its commencement until further research resolves two key uncertainties. This chapter will first provide future research avenues to deal with these uncertainties. Hereafter, this chapter will conclude with several policy recommendations for Dutch policymakers concerning the transition into hydrogen FC HDTs.

11.1 Research recommendations

For policymakers to consider initiating a subsidy program exceeding the current proposed budget, first, further research is recommended. Without additional investigation, investing such a significant number of resources carries considerable risk and may be unwise. This paragraph proposes several research topics aimed at enhancing the comprehensive understanding of the subsidy program. Eventually, these new insights might enable policymakers to make more informed decisions, based on more accurate projected outcomes.

First, to gain a deeper understanding of the expected fixed costs of hydrogen FC HDTs, further research on the development of economies of scale is needed. This research topic holds significant importance, as highlighted by the sensitivity analysis, which demonstrated the substantial influence of fixed costs on the model's outcome. Future research should scrutinize the developments of economies of scale, enabling policymakers to formulate more precise policy alternatives. Unlike this thesis, which assumes a specific market share of hydrogen in the long-haul transport sector to predict the economies of scale, future research may not be bound by the same viewpoint. For example, researching the annual production volume required to accelerate economies of scale could help determine if the Netherlands can transition independently, or if its production capacity is too limited for such acceleration. This method might be more suitable as it immediately implements the feasibility of implementing hydrogen FC HDTs within a certain scope.

Furthermore, a comprehensive understanding of additional infrastructure costs is essential. Presently, the thesis solely addresses the installation expenses of hydrogen fueling stations, overlooking potential costs like reinforcement and maintenance of gas pipes. Researchers should investigate other expenses to provide a complete financial breakdown of infrastructure costs. With this comprehensive breakdown, a more accurate NPV projection can be achieved, facilitating clearer decision-making for policymakers.

In conclusion, delving into these two research avenues is crucial owing to the significant uncertainties surrounding economies of scale and infrastructure development. By acquiring further insights into both factors, a more precise NPV can be calculated, thereby enabling a more informed assessment of the subsidy program's social viability. The next paragraph will further recommend policymakers on these issues.

11.2 Recommendations for policymakers

As mentioned in the conclusion, economies of scale are assumed to depend on the market share of hydrogen FC HDTs. This assumption carries significant uncertainty, as various external factors such as international demand, technological advancements, and European regulations could influence economies of scale. Moreover, the scenario analysis revealed that less favourable outcomes could lead to substantial subsidy requirements possibly without any social return on investment, again underscoring the importance of comprehensive research before implementing such a program. With established economies of scale, the fixed costs can be accurately projected, enabling policymakers to make more informed decisions.

Furthermore, due to insufficient hydrogen infrastructure cost data, including the absence of expenses such as pipeline reinforcement and maintenance costs, a comprehensive financial understanding of the social costs is lacking so far. This thesis proposes that policymakers should first allow researchers to comprehensively analyse the financial breakdown of infrastructure costs. As demonstrated in this thesis, delaying the start of the subsidy program significantly reduces the likelihood of achieving a socially viable subsidy program. Hence, research on both economies of scale development and infrastructure costs should be conducted soon.

Besides, this research indicated that the proposed subsidy budget of 200 million euros is insufficient to fully transition hydrogen FC HDTs toward achieving an emission-free long-haul transport sector by 2050. Thus, if policymakers aim to facilitate a transition to hydrogen, it is imperative to increase the subsidy budget from 200 million euros to at least 4 billion euros, for the scenario where hydrogen FC HDTs are deployed for trips exceeding 150 kilometres. Additionally, if policymakers intend to extend the utilization of hydrogen FC HDTs to cover even longer distances, including trips exceeding 50 kilometres, a reserve of at least 12 billion euros should be allocated. In case such a budget increase is not possible, redirecting efforts toward alternative zero-emission solutions or collaborating with European partners to distribute the subsidy across multiple countries would be more advantageous.

To conclude, given this study's national focus on the long-haul HDT sector, it is important to acknowledge that countries beyond the Netherlands also require hydrogen infrastructure, given the international nature of long-haul trips. Without such infrastructure, hydrogen FC HDTs would face significant limitations in refuelling outside the Netherlands, likely reducing the demand for hydrogen HDTs. Hence, at least to some extent, European collaboration is necessary for a feasible widespread adoption of hydrogen HDTs. Seeking collaboration within Europe to collectively accelerate economies of scale through a shared subsidy program would reduce the relative costs of such a program for each participating country. Moreover, as the same uncertainties regarding economies of scale development and the financial breakdown of the infrastructure cost apply in an international context, starting collective European research would be advisable. Ultimately, the transition into hydrogen FC HDTs in the Netherlands requires a comprehensive and collective effort from EU-wide researchers and policymakers.

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Appendix A: List of variables in Social Cost-Benefit Analysis

Table 16: *List of variables in Social Cost-Benefit Analysis*

Variable	**Unit**	**Value**	**Source**
Discount rate	%	2.25	PBL, 2013
European target	% in respect to 2019	90	European Commission, 2023
Electric truck usage	%	40 or 75	CBS, 2022
Increasement of trucks due to demand per year	%/year	1,06	CBS, 2023
Registered Heavy Duty Vehicles	Number of trucks	146.500	CBS, 2023
Distance covered by Dutch trucks (trekkers, 2019)	km	78.000	CBS, 2022
Fuel price diesel	Euro/l	1.83	Average fuel price in the year 2023 (CBS, 2023)
Life age of trekkers	Years	8	The average is actually is 7.6 years. This makes calculations difficult and therefore the life age is set at 8 years (CBS, 2015)
Fuel price development nominal diesel price EU (1980 - 2018)	%/year	0.11%	European Environment Agency, 2023
Retail price diesel truck	Euro	104.000	Basma, 2021
Fuel consumption	l/km	0.288	H2 accelerate, 2022
Fuel consumption development	l/km/year	From 0.288 towards 0.275 in the year 2050	H2 accelerate, 2022
Maintenance cost diesel	Euro/km	0.19	H2 accelerate, 2022
Diesel emission	g CO_2/l	2.736	CO_2emissiefactoren, 2023
Maintenance cost hydrogen	Euro/km	0.19	H2 accelerate, 2022
Maintenance costs hydrogen development	Euro/km	0.19 towards 0.14 in the year 2050	Basma et al., 2021
Fuel price hydrogen	Euro/kg	11 (in the year 2023)	TNO, 2022
Fuel price development	Euro/kg/year	2023-2025: -€ 0.50 2026-2030: -€ 0.20 2031-2050: -€ 0.08	TNO, 2022
Retail price H2 trucks	Euro/truck		H2 accelerate, 2022
Retail price H2 trucks development	Euro/truck/year	2024-2026: -€ 94,000 2026-2033: -€ 18,000 2033 – 2037: -€ 10,250	H2 accelerate, 2022
Fuel Consumption	Kg/km	0.07 (in 2023)	H2 accelerate, 2022
Fuel consumption developments	Kg/km	From 0.07 towards 0.06 in the year 2050	H2 accelerate, 2022

Reduction of price after a full industrialization	%	0.5	Garsten, 2023
Emission hydrogen production	g CO$_2$/kg H2	0	Derived from the interview with RVO
CO$_2$ social cost	Euro/gram CO$_2$	2021 € 77 2030: € 104 2050: € 208	CE Delft, 2023
NO$_x$ Social cost	Euro/gram NO$_x$	€ 29,9	CE Delft, 2023
PM-2.5 Social cost	Euro/gram PM$_{2.5}$	€ 121	CE Delft, 2023
PM-10 social cost	Euro/gram PM$_{10}$	€ 69,3	RWS, 2020
Truck NOx emission	Gram NO$_x$	1.2	CE Delft, 2022
Truck PM2.5 emission	Gram PM$_{2.5}$/km	0.133	CE Delft, 2022
Truck Pm10 emission	Gram PM$_{10}$/km	0.186	CE Delft, 2022

Appendix B: Results of the Social Cost-Benefit Analysis

This appendix shows the graphs of the following result for each subsidy:

- Total cost of ownership of hydrogen fuel cell heavy-duty trucks development from 2023 – 2050.
- Total cost of ownership difference of hydrogen fuel cell and diesel heavy-duty trucks development from 2023 – 2050.
- Year of implementing economies of scale
- Fleet share development of hydrogen fuel cell and diesel heavy-duty trucks from 2023 – 2050.
- Annual budget requirement from 2023 – 2050.
- Annual CO_2 emission reduction from 2023 – 2050.
- Cash flow from 2023 – 2050.

B.1 Early subsidy

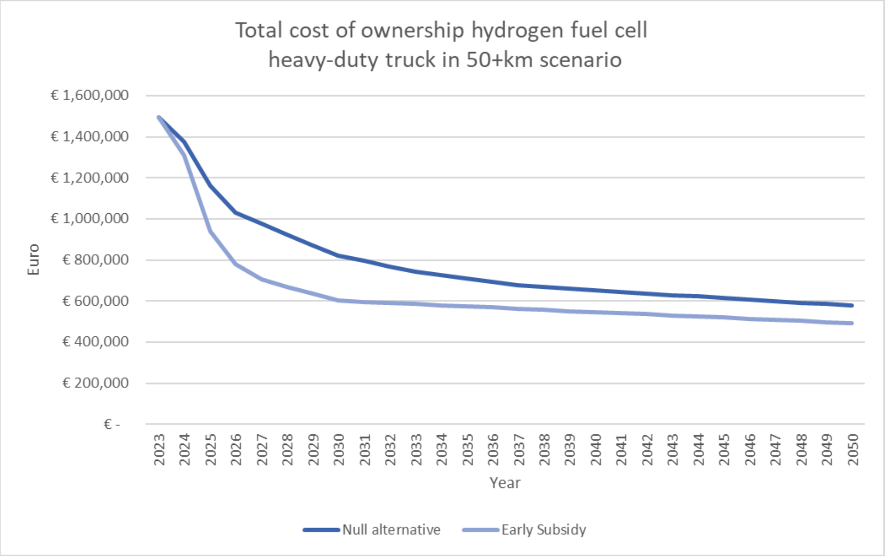


Figure 11.1: *Total cost of ownership of hydrogen fuel cell heavy-duty trucks in the 50+km scenario 2023 – 2050.*

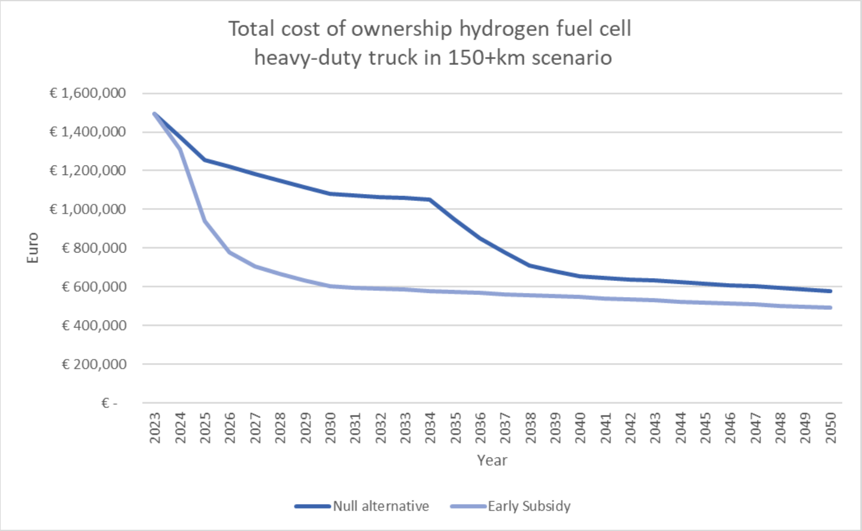


Figure 11.2: *Total cost of ownership of hydrogen fuel cell heavy-duty trucks in the 150+km scenario 2023 – 2050.*

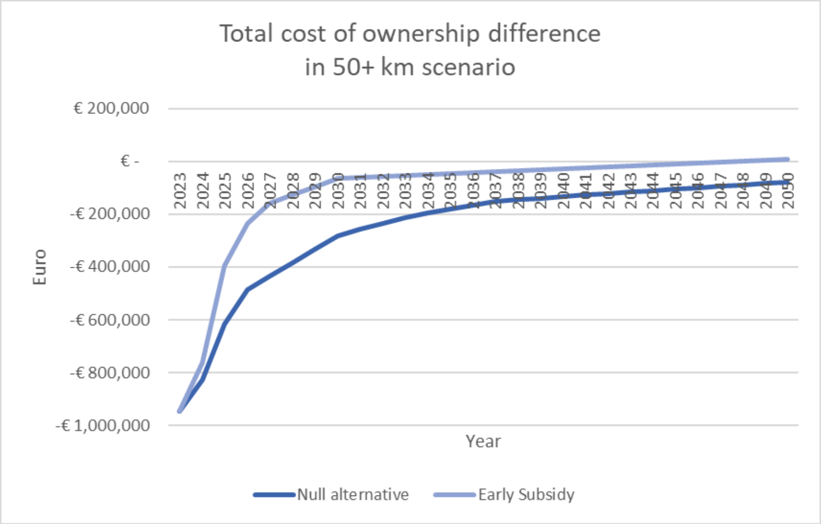


Figure 12.1: *Total cost of ownership difference of hydrogen fuel cell heavy-duty trucks in early subsidy relation to diesel heavy-duty trucks in the 50+km scenario 2023 – 2050.*

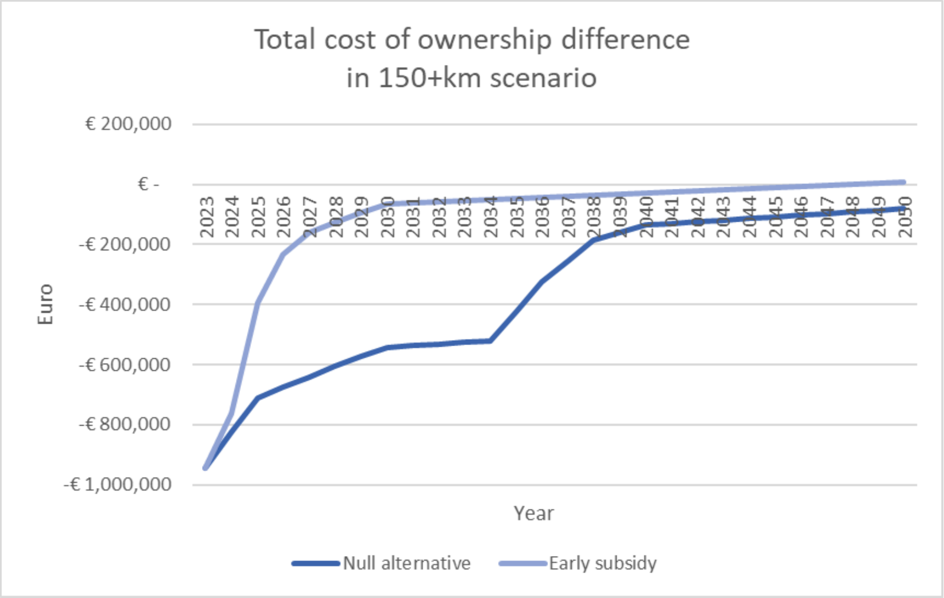


Figure 12.2: *Total cost of ownership difference of hydrogen fuel cell heavy-duty trucks in early subsidy in relation to diesel heavy-duty trucks in the 150+km scenario 2023 – 2050.*

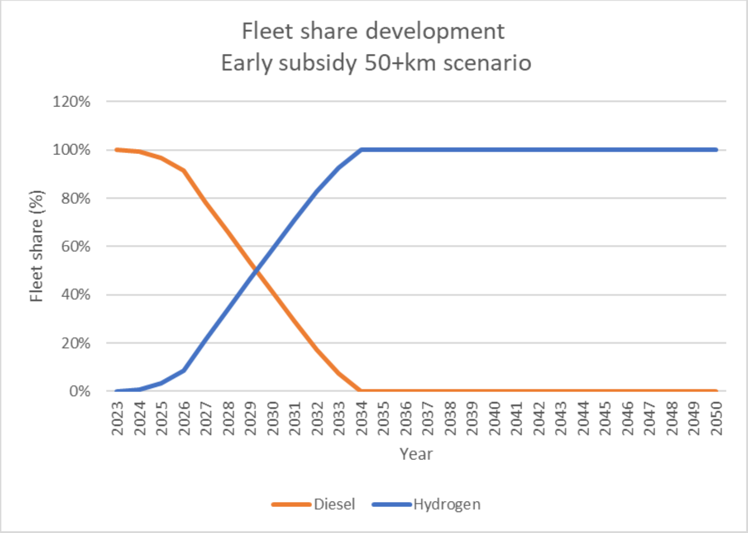


Figure 13.1: *Fleet share development of the early subsidy in the 50+km scenario 2023 – 2050.*

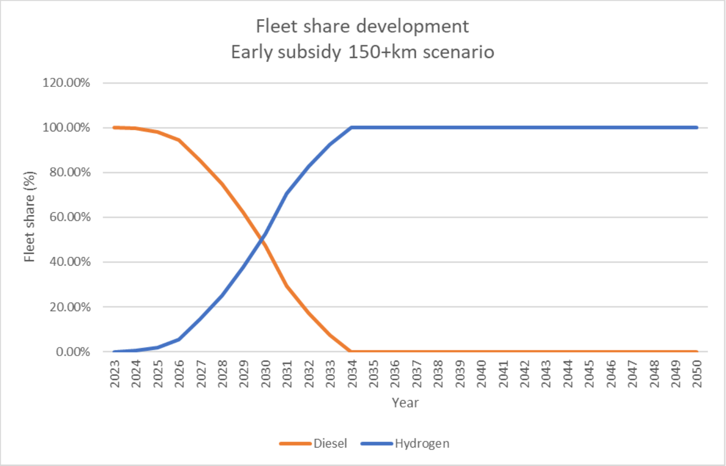


Figure 13.2: *Fleet share development of the early subsidy in the 150+km scenario 2023 – 2050.*

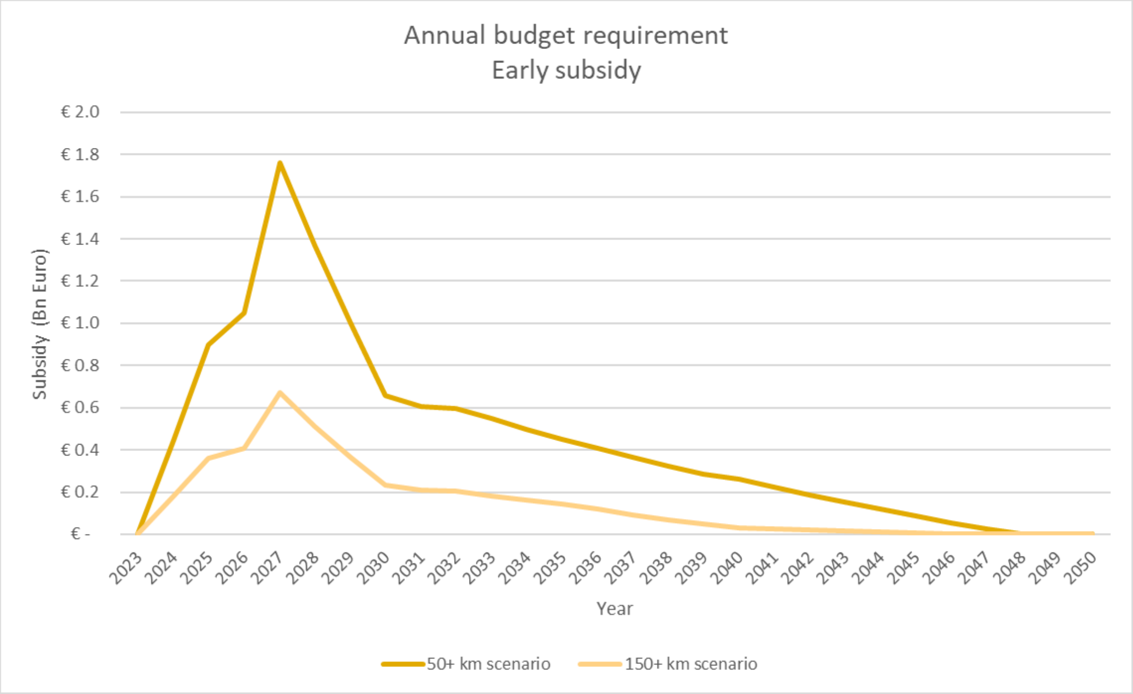


Figure 14: *Annual budget requirement early subsidy in billion euros.*

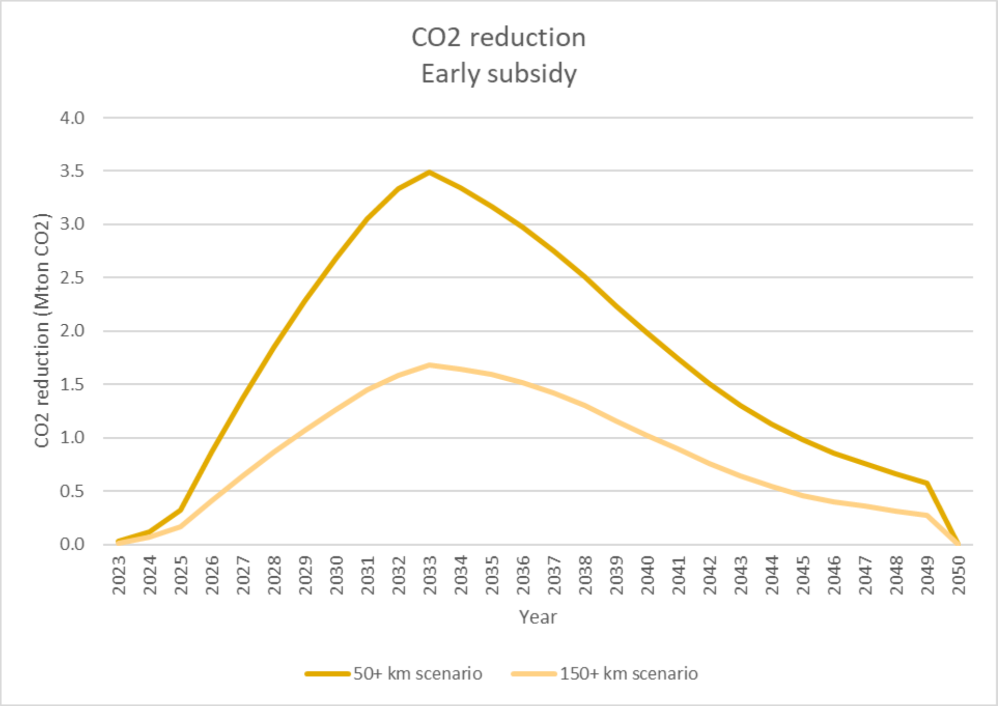


Figure 15: *CO_2 emission reduction early subsidy in Mton CO_2.*

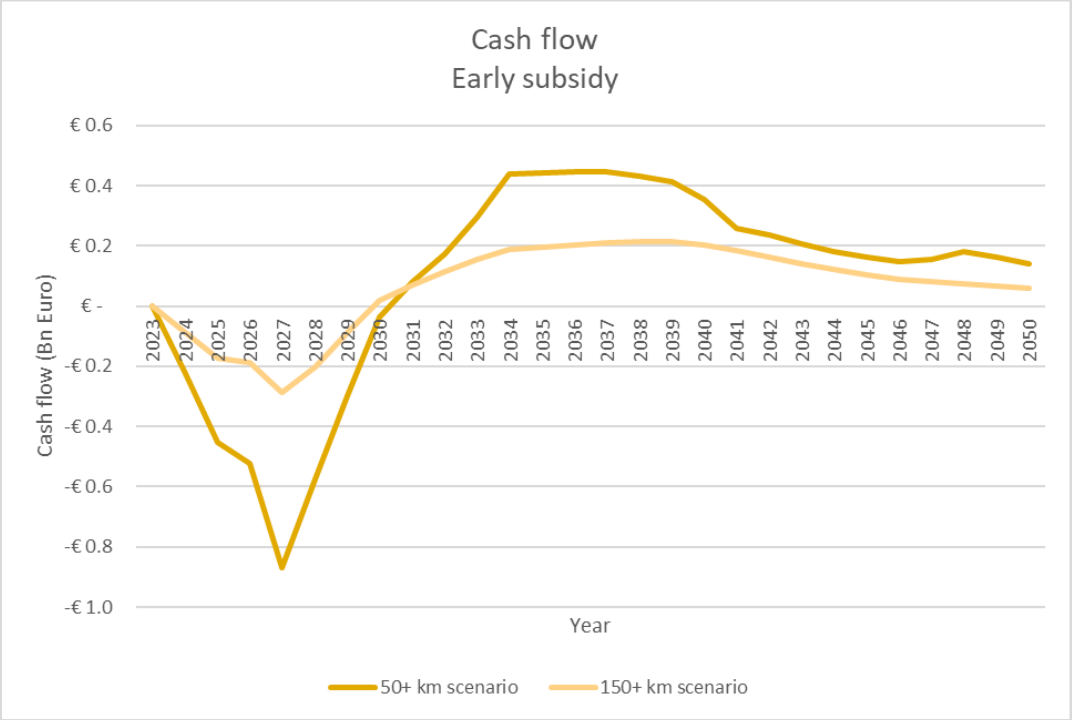


Figure 16: *Cashflow of early subsidy in billion euros.*

B.2 Middle subsidy

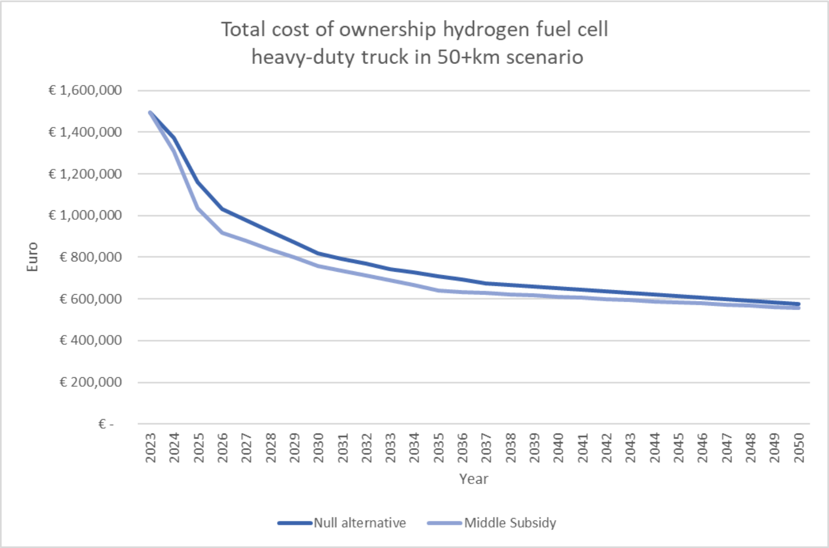


Figure 17.1: *Total cost of ownership of hydrogen fuel cell heavy-duty trucks in the 50+km scenario 2023 – 2050.*

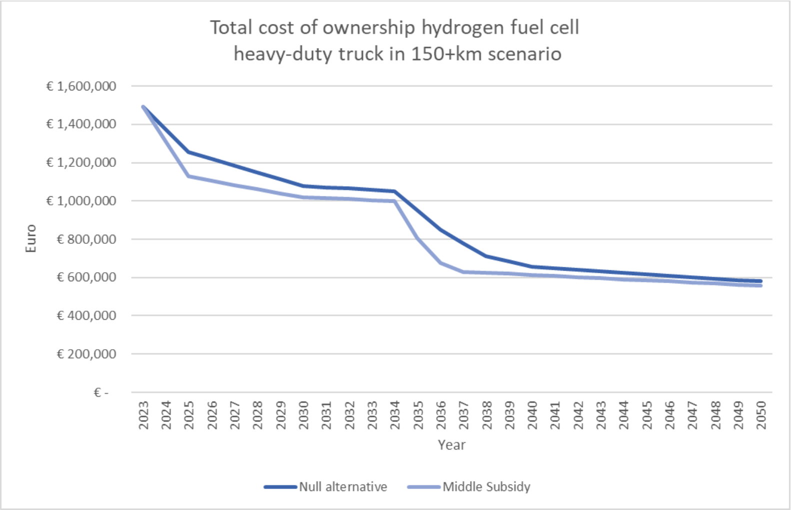


Figure 17.2: *Total cost of ownership of hydrogen fuel cell heavy-duty trucks in the 50+km scenario 2023 – 2050.*

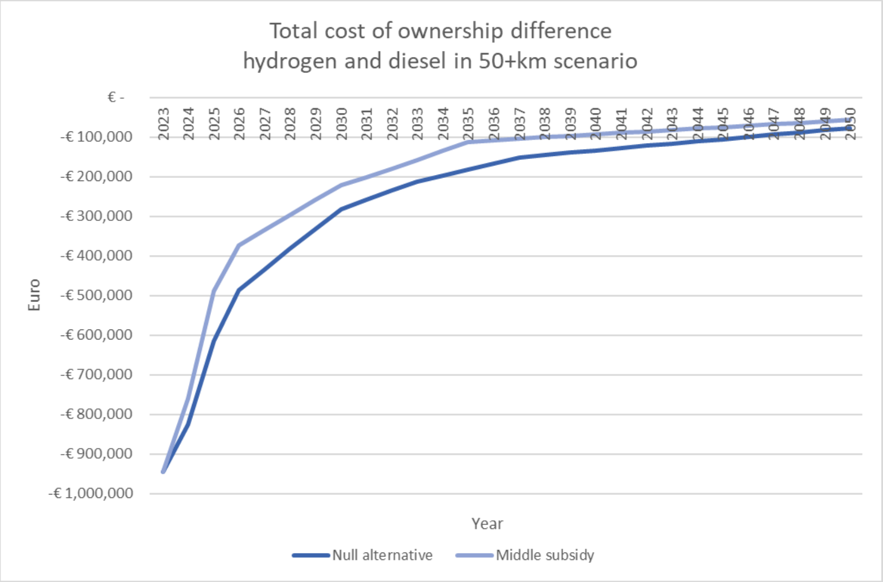


Figure 18.1: *Total cost of ownership difference of hydrogen fuel cell heavy-duty trucks in middle subsidy in relation to diesel heavy-duty trucks in the 50+km scenario 2023 – 2050.*

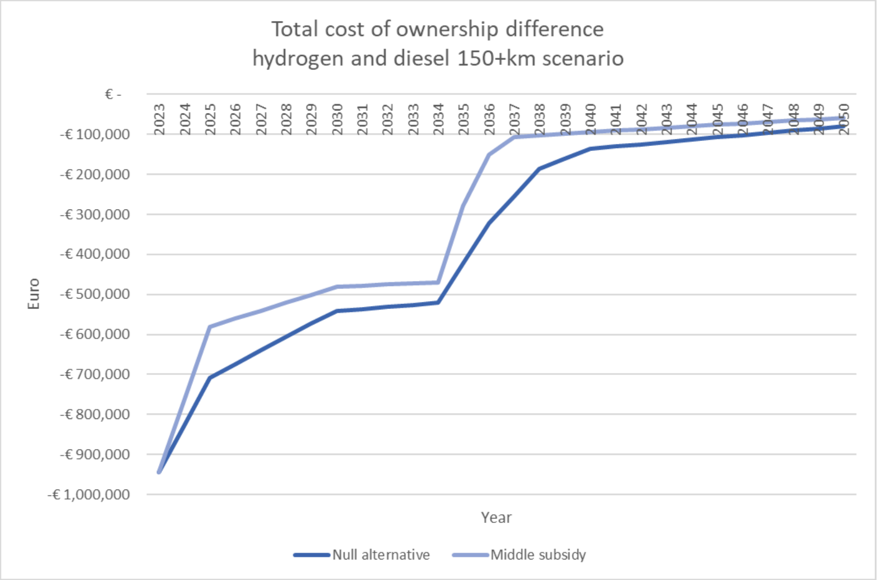


Figure 18.2: *Total cost of ownership difference of hydrogen fuel cell heavy-duty trucks in middle subsidy in relation to diesel heavy-duty trucks in the 50+km scenario 2023 – 2050.*

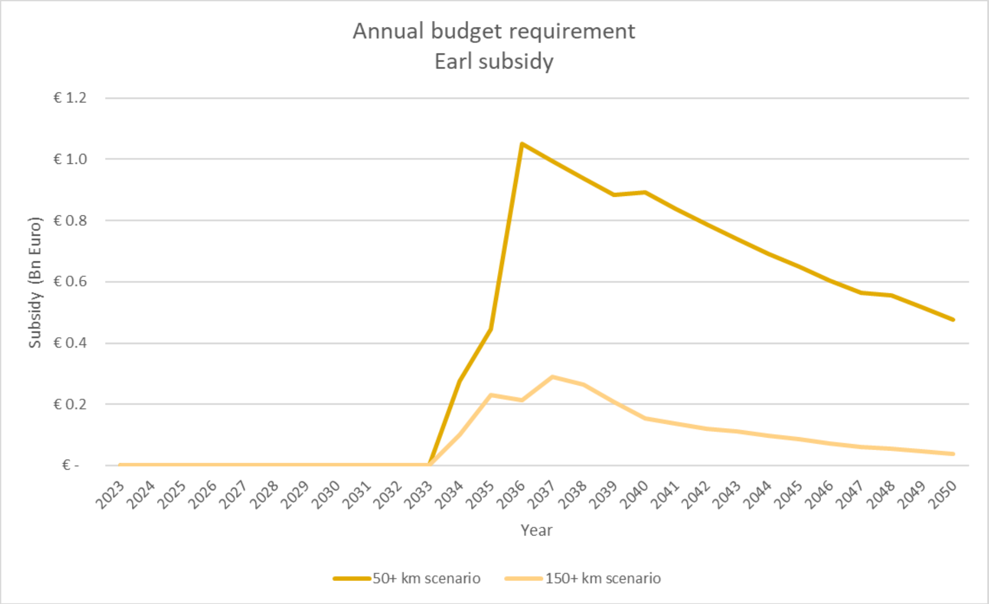


Figure 19: *Annual budget requirement middle subsidy in billion euros.*

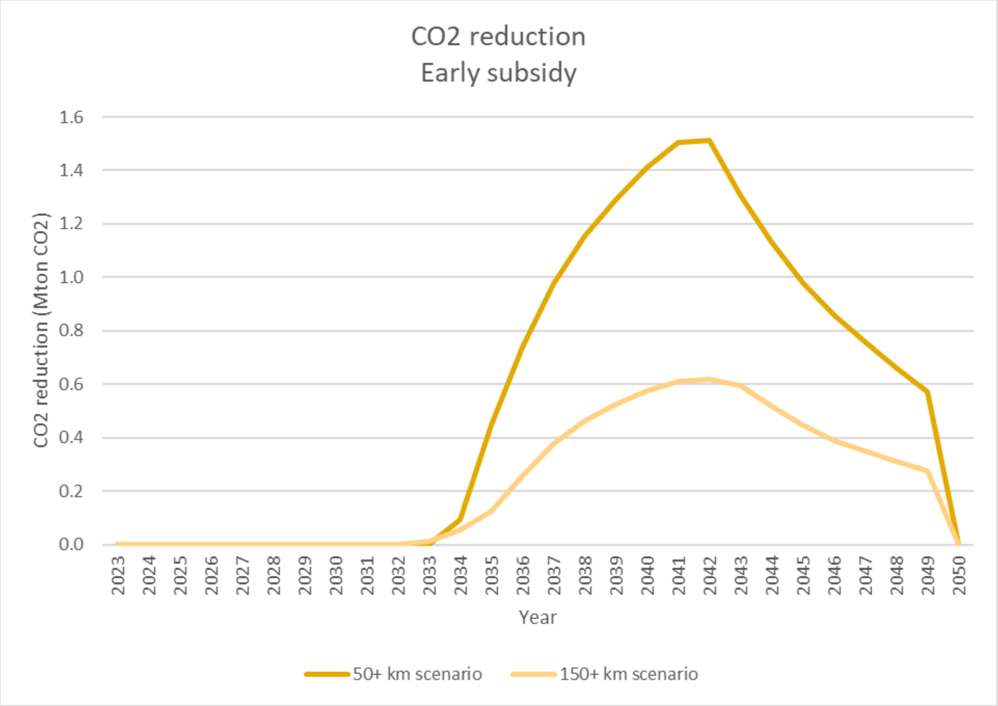


Figure 20: *CO_2 emission reduction middle subsidy in Mton CO_2.*

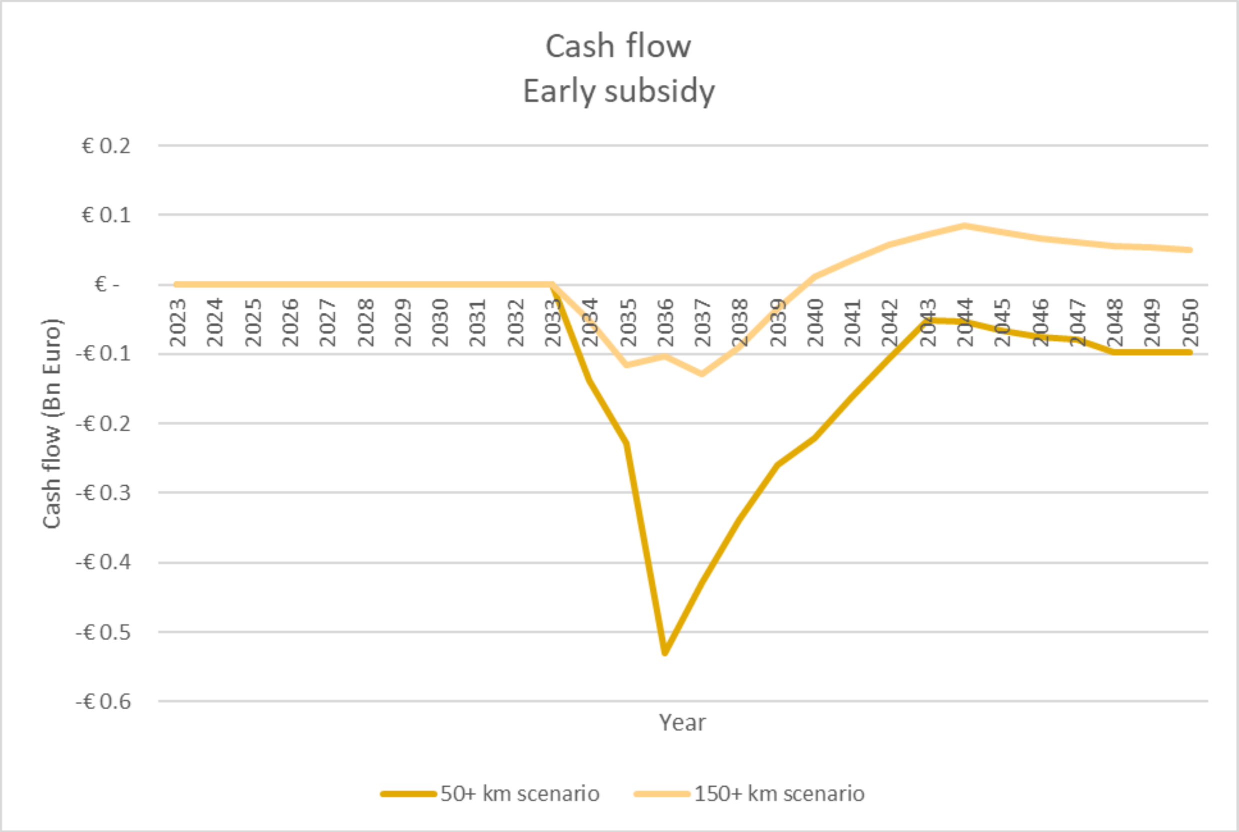


Figure 21: *Cashflow of middle subsidy in billion euros.*

B.3 Late subsidy

For the late subsidy, the economies of scale are equal to the null alternative. Hence, only the annual budget requirements, CO_2 reduction and cash flow are presented.

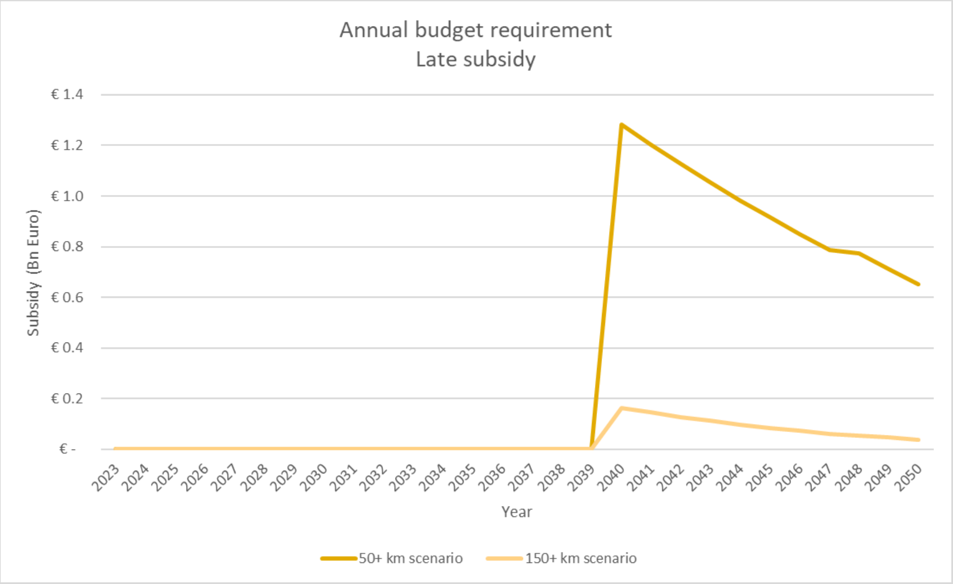


Figure 22: *Annual budget requirement late subsidy in billion euros.*

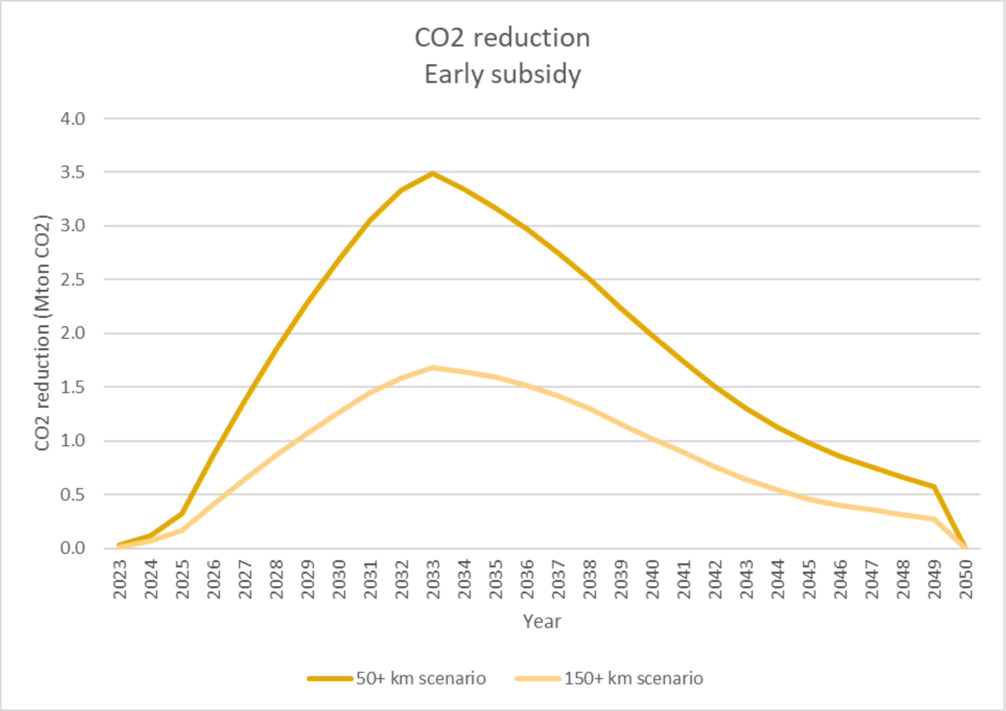


Figure 23: *CO_2 emission reduction late subsidy in Mton CO_2.*

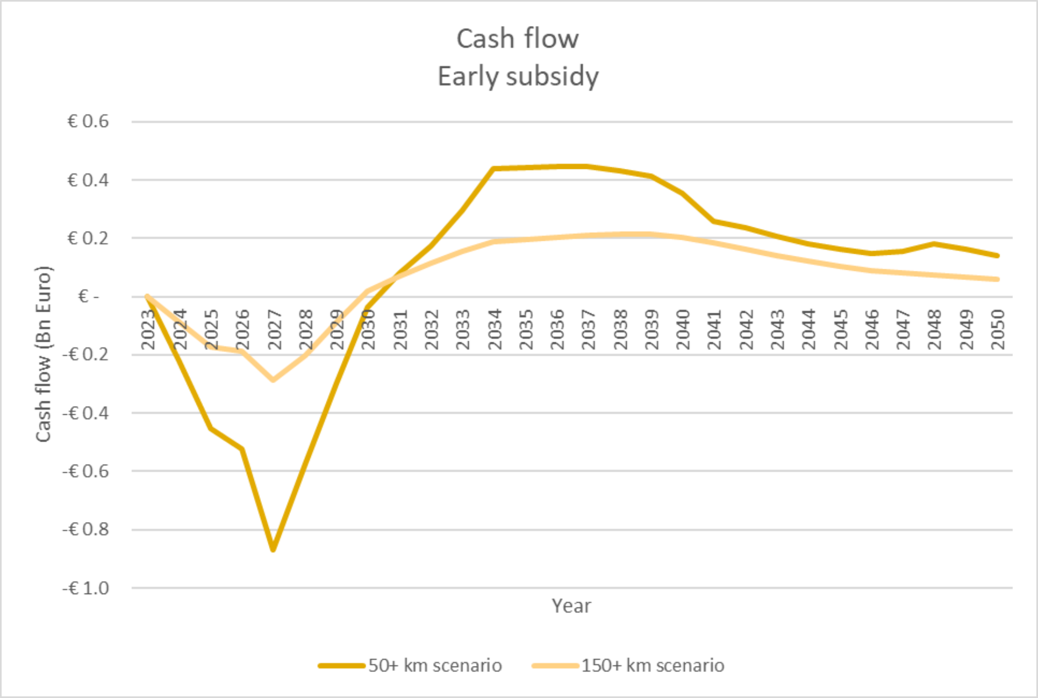
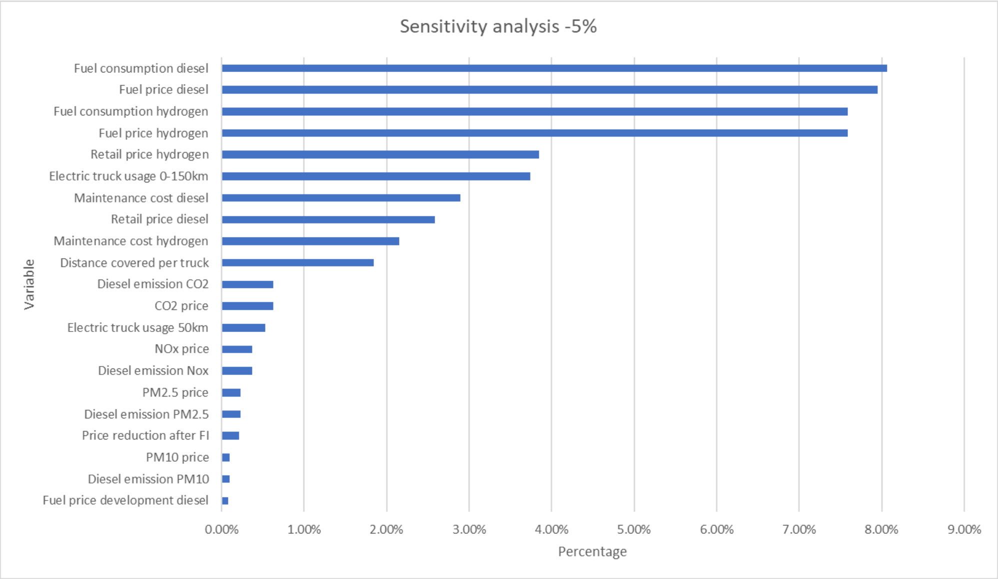


Figure 24: *Cashflow of late subsidy in billion euros.*

Appendix C: Sensitivity analysis

Figure 25 visually depicts the result of the sensitivity analysis, with variables sorted in descending order of impact, from the most influential at the top to the least influential at the bottom. After the figures, the results are shown in table format. These tables display the outcomes of both the 50+km and 150+km scenarios, showcasing the impact of a -5% variable value and a +5% variable value.



This figure illustrates the percentage change in Net Present Value resulting from a -5% adjustment to each individual variable in the model. Variables exerting the greatest influence are positioned at the top, while those with lesser impact are located at the bottom.

Figure 25.1: *Result of sensitivity analysis -5% variable value*

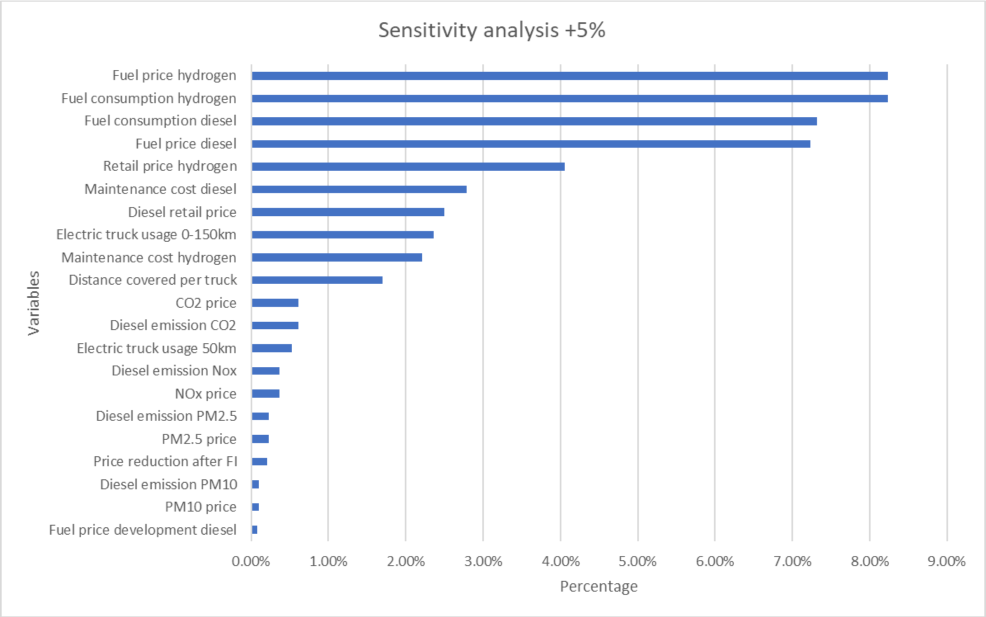


Figure 25.2: *Result of sensitivity analysis +5% variable value*

Table 17.1: *Result of sensitivity analysis +5% variable value in 50+km scenario*

Variable	**Early subsidy**	**Middle subsidy**	**Late subsidy**	**Optimalization subsidy**	**Average**
Distance covered per truck	-0.86%	-1.99%	-3.64%	-0.26%	-1.69%
Electric truck usage 50km	0.14%	-0.06%	-0.36%	2.40%	0.53%
Electric truck usage 0-150km	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel price hydrogen	3.37%	8.42%	13.83%	1.68%	6.82%
Retail price hydrogen	1.67%	4.31%	7.63%	0.11%	3.43%
Price reduction after FI	-0.09%	-0.18%	-0.37%	-0.36%	-0.25%
Fuel consumption hydrogen	3.37%	8.42%	13.83%	1.68%	6.82%
Maintenance cost hydrogen	0.98%	2.29%	4.11%	0.43%	1.95%
Fuel price diesel	-3.13%	-8.38%	-15.82%	-1.35%	-7.17%
Fuel price development diesel	-0.02%	-0.09%	-0.19%	-0.01%	-0.08%
Diesel retail price	-1.05%	-2.75%	-5.11%	-0.46%	-2.34%
Fuel consumption diesel	-3.16%	-8.49%	-16.10%	-1.36%	-7.28%
Maintenance cost diesel	-1.17%	-3.08%	-5.73%	-0.51%	-2.62%
CO_2 price	-0.30%	-0.73%	-1.13%	-0.14%	-0.57%
NOx price	-0.18%	-0.43%	-0.69%	-0.08%	-0.34%
PM10 price	-0.05%	-0.11%	-0.18%	-0.02%	-0.09%
PM2.5 price	-0.11%	-0.27%	-0.43%	-0.05%	-0.22%
Diesel emission CO_2	-0.30%	-0.73%	-1.13%	-0.14%	-0.57%
Diesel emission NO_x	-0.18%	-0.43%	-0.69%	-0.08%	-0.34%
Diesel emission PM10	-0.05%	-0.11%	-0.18%	-0.02%	-0.09%
Diesel emission PM2.5	-0.11%	-0.27%	-0.43%	-0.05%	-0.22%

Table 17.2: *Result of sensitivity analysis -5% variable value in 150+km scenario.*

Variable	**Early subsidy**	**Middle subsidy**	**Late subsidy**	**Optimalization subsidy**	**Average**
Distance covered per truck	0.82%	1.84%	3.29%	0.26%	1.55%
Electric truck usage 50km	0.14%	-0.06%	-0.36%	2.40%	0.53%
Electric truck usage 0-150km	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel price hydrogen	-3.12%	-8.78%	-16.30%	-1.47%	-7.42%
Retail price hydrogen	-1.62%	-4.45%	-8.36%	-0.10%	-3.63%
Price reduction after FI	0.09%	0.18%	0.36%	0.34%	0.24%
Fuel consumption hydrogen	-3.12%	-8.78%	-16.30%	-1.47%	-7.42%
Maintenance cost hydrogen	-0.96%	-2.34%	-4.33%	-0.41%	-2.01%
Fuel price diesel	3.30%	7.91%	13.32%	1.53%	6.51%
Fuel price development diesel	0.02%	0.08%	0.19%	0.01%	0.08%
Diesel retail price	1.06%	2.68%	4.80%	0.48%	2.26%
Fuel consumption diesel	3.32%	7.99%	13.49%	1.54%	6.58%
Maintenance cost diesel	1.18%	2.99%	5.35%	0.53%	2.51%
CO_2 price	0.30%	0.71%	1.09%	0.14%	0.56%
NOx price	0.18%	0.42%	0.68%	0.08%	0.34%
PM10 price	0.05%	0.11%	0.18%	0.02%	0.09%
PM2.5 price	0.11%	0.27%	0.43%	0.05%	0.21%
Diesel emission CO_2	0.30%	0.71%	1.09%	0.14%	0.56%
Diesel emission NO_x	0.18%	0.42%	0.68%	0.08%	0.34%
Diesel emission PM10	0.05%	0.11%	0.18%	0.02%	0.09%
Diesel emission PM2.5	0.11%	0.27%	0.43%	0.05%	0.21%

Table 17.3: *Result of sensitivity analysis +5% variable value in 50+km scenario.*

Variable	Early subsidy	Middle subsidy	Late subsidy	Optimalization subsidy	Average
Distance covered per truck	-0.81%	-2.04%	-4.35%	-0.83%	-2.01%
Electric truck usage 50km	0.00%	0.00%	0.00%	0.00%	0.00%
Electric truck usage 0-150km	0.12%	0.56%	-0.04%	14.34%	3.74%
Fuel price hydrogen	3.17%	7.13%	18.06%	5.06%	8.35%
Retail price hydrogen	1.62%	4.00%	9.78%	1.68%	4.27%
Price reduction after FI	-0.09%	-0.18%	-0.29%	-0.16%	-0.18%
Fuel consumption hydrogen	3.17%	7.13%	18.06%	5.06%	8.35%
Maintenance cost hydrogen	0.91%	2.14%	5.12%	1.24%	2.35%
Fuel price diesel	-2.96%	-8.75%	-19.25%	-3.94%	-8.73%
Fuel price development diesel	-0.02%	-0.09%	-0.23%	-0.03%	-0.09%
Diesel retail price	-0.99%	-2.72%	-6.23%	-1.38%	-2.83%
Fuel consumption diesel	-2.98%	-8.89%	-19.59%	-3.97%	-8.86%
Maintenance cost diesel	-1.10%	-3.06%	-6.98%	-1.54%	-3.17%
CO_2 price	-0.29%	-0.71%	-1.35%	-0.36%	-0.68%
NOx price	-0.17%	-0.42%	-0.82%	-0.21%	-0.41%
PM10 price	-0.04%	-0.11%	-0.21%	-0.05%	-0.10%
PM2.5 price	-0.11%	-0.26%	-0.51%	-0.13%	-0.25%
Diesel emission CO_2	-0.29%	-0.71%	-1.35%	-0.36%	-0.68%
Diesel emission NOx	-0.17%	-0.42%	-0.82%	-0.21%	-0.41%
Diesel emission PM10	-0.04%	-0.11%	-0.21%	-0.05%	-0.10%
Diesel emission PM2.5	-0.11%	-0.26%	-0.51%	-0.13%	-0.25%

Table 17.4: *Result of sensitivity analysis +5% variable value in 150+km scenario.*

	Early subsidy	**Middle subsidy**	**Late subsidy**	**Optimalization subsidy**	**Average**
Distance covered per truck	0.77%	1.82%	3.93%	0.82%	1.84%
Electric truck usage 50km	0.00%	0.00%	0.00%	0.00%	0.00%
Electric truck usage 0-150km	-0.11%	-0.51%	0.04%	-8.86%	-2.36%
Fuel price hydrogen	-2.97%	-9.14%	-19.84%	-4.22%	-9.04%
Retail price hydrogen	-1.57%	-4.53%	-10.34%	-1.50%	-4.48%
Price reduction after FI	0.09%	0.18%	0.29%	0.16%	0.18%
Fuel consumption hydrogen	-2.97%	-9.14%	-19.84%	-4.22%	-9.04%
Maintenance cost hydrogen	-0.90%	-2.30%	-5.28%	-1.19%	-2.42%
Fuel price diesel	3.08%	6.80%	17.30%	4.66%	7.96%
Fuel price development diesel	0.02%	0.09%	0.23%	0.03%	0.09%
Diesel retail price	0.99%	2.49%	5.99%	1.46%	2.73%
Fuel consumption diesel	3.10%	6.87%	17.53%	4.70%	8.05%
Maintenance cost diesel	1.11%	2.77%	6.68%	1.64%	3.05%
CO_2 price	0.29%	0.68%	1.31%	0.36%	0.66%
NOx price	0.17%	0.41%	0.81%	0.21%	0.40%
PM10 price	0.04%	0.11%	0.21%	0.05%	0.10%
PM2.5 price	0.11%	0.26%	0.51%	0.13%	0.25%
Diesel emission CO_2	0.29%	0.68%	1.31%	0.36%	0.66%
Diesel emission NO_x	0.17%	0.41%	0.81%	0.21%	0.40%
Diesel emission PM10	0.04%	0.11%	0.21%	0.05%	0.10%
Diesel emission PM2.5	0.11%	0.26%	0.51%	0.13%	0.25%

Appendix D: Variables in scenario analysis

Table 17.4: *Result of sensitivity analysis +5% variable value in 150+km scenario.*

Variables	**Low**	**Variable in standard CBA**	**High**	**Explanation on value**
Fuel price diesel	€ 1.72/l	€ 1.83/l	€ 1.94/l	The low value corresponds to the average diesel fuel price derived from the four lowest prices per month. The high price corresponds to the difference between the low and the average, with the assumption that the high value maintains the same difference (CBS, 2023).
Fixed cost Hydrogen	R&D phase: € 471,000 Industrial scale up: € 283,000 Sustainable growth: € 182,000 Full industrialization: € 148,000	R&D phase: € 534,000 Industrial scale up: € 346,000 Sustainable growth: € 220,000 Full industrialization: € 179,000	R&D phase: € 579,000 Industrial scale up: € 409,000 Sustainable growth: € 247,000 Full industrialization: € 242,000	H2accelerate (2022) introduced three potential scenarios: favorable, unfavorable, and average/likely scenarios. The favorable scenario reflects low values, while the unfavorable scenario reflects high values.
Fuel price hydrogen	20-4.5 €/l	20-7.5 €/l	20 – 12 €/l	The thesis utilizes the best-case scenario of green hydrogen production to estimate the low value. The deviation from this best-case scenario to the expected value is determined for the high value (TNO, 2022).

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