

Reducing CO₂-emissions of Port of Rotterdam hinterland transport by truck

Analyzing the dynamics of adoption of technologies that reduce the carbon intensity of energy used by trucks

MSc Thesis

Laurens de Jonge



Reducing CO₂-emissions of Port of Rotterdam hinterland transport by truck

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energy used by trucks

by

Laurens de Jonge

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Thesis committee:	Prof. dr. ir. L. A. Tavasszy	TU Delft, chair
	Dr. ir. S. E. Tanzer	TU Delft, first supervisor
	Dr. M. D. Kubli	TU Delft, second supervisor
	Ir. J. Schmid	TU Delft, advisor
Student number:	4967526	

Preface

With the completion of this thesis, I conclude the final chapter of my master's programme in Engineering and Policy Analysis at TU Delft. After a long period of virtual learning during the COVID-19 pandemic, this programme formed my first real immersion in the Delft student community. I am grateful for what I have learned from the course content and my fellow students, that have strengthened my knowledge and confidence for my next steps beyond student life.

The search for a thesis topic was steered by my desire to utilize system dynamics as a research method. For me, this methodology is able to effectively inform policymakers, by elegantly capturing complex systemic behaviour. In a world that is increasingly guided by short-term policies, research utilizing system dynamics can form an important counterweight that includes long-term perspectives for the complex problems we face today. It was especially interesting to use system dynamics for the green transition, a topic that is often characterized by defining it as a trade-off between economic growth and reduced carbon emissions. My motivation for this research stemmed from the idea that these two factors can co-exist. By studying the concrete example of truck hinterland transport for the Port of Rotterdam, this could be made quantifiable in enough detail for a concrete case.

The individuality of the thesis process proved challenging. During the master's programme in Engineering and Policy Analysis and other experiences I had primarily gotten accustomed to group-work. Collaborating in a group brings the advantages of open discussion about research difficulties, as well as tapping into the various strengths of group members. The absence of these factors have allowed me to observe my individual qualities as a researcher, as well as facing and strengthening my weaknesses.

I owe a great deal of gratitude to those that have supported me during this process.

To my advisor, Jonathan Schmid, who has always been patient, encouraging and engaged with my research. I am curious to see where he can take the research on this topic within his own research. I would also like to thank my first supervisor, Samantha Tanzer, especially for her help with formulating a flowing storyline for this broad (and sometimes overwhelming) research topic. To my second supervisor, Merla Kubli, for her helpful advice on concrete system dynamics issues. Also, I would like to thank Lóri Tavasszy, whose sharp feedback and professional perspective strengthened both the structure and the substance of this work.

To the friends that I have co-worked with, especially during the lonely summer months. Thanks for keeping me motivated and giving me a change of scenery. I also owe a lot to your willingness to discuss my thesis, which has allowed me to zoom-out and focus on the broader picture.

To my friends and family, who have checked in with me and cared for me, even when I was so absorbed by my work that I had little to give back.

To my baby nieces, as well as the two young cats that have supported me in the final stages of this process. Even though I expected no in-depth thesis discussions with you, you showed me with unconditional love that there was more in life beyond the thesis.

To my father, who has passed away last year. He has always been a large supporter of my academic career and patiently stimulated the exploration of my broad interests. Due to the time it took to discover these various interests he has never seen the end of my academic career, but I am sure that he would be proud of this achievement.

Finally, to anyone reading this thesis: I have discovered models to be discussion-provoking tools rather than predictive instruments. Therefore, I can only hope that reading this thesis leads you to reflect on this important topic and stimulate the actors involved towards collaborative action.

*Laurens de Jonge
Delft, September 2025*

Executive Summary

Opening Problem Statement

The decarbonization of container transport by trucks is a critical challenge in the transition to a decarbonized transport system. As the biggest logistics hub in Europe, the Port of Rotterdam is essential to lowering CO₂-emissions from freight transportation in its hinterland. With trucks being the hinterland modality with the highest relative CO₂-emissions, and the size of hinterland truck transport expected to increase, decarbonization of this modality is researched in this study in order to reach the Port of Rotterdam goal of becoming carbon-neutral by 2050. This research studies the adoption of three carbon intensity of energy reducing technologies - Battery Electric Trucks, Fuel-Cell Electric Trucks and E-diesel - and the role that these technologies can play in the decarbonization of Port of Rotterdam truck hinterland transport.

Context and Gap

Although other research has looked at several decarbonization tactics at once, this study focuses on comparing three truck-specific technologies that have a lower carbon intensity of energy. Technology-specific dynamic system-level models that incorporate governmental interventions over time, infrastructure availability, adoption behaviour and the price elasticity of hinterland transportation are scarce. Policymakers and industry stakeholders are less able to foresee transition routes and create efficient support measures as a result of this gap. Furthermore, successful transition depends on the local context of the energy hub under analysis, which is why the Port of Rotterdam has been chosen as a specific case study.

Objective and Research Question

The research investigates which systemic behaviours should be targeted by which policy interventions and what the most effective policy timing is. It addresses the following research question:

What is the most viable technology for the reduction of the carbon intensity of energy for trucks involved in the dynamic hinterland transport of the port of Rotterdam?

To answer this, the study uses a mixed-methods design. Insights from literature and model outcomes are validated with experts to assure their alignment with the real world. The aim is to clarify how adoption of carbon intensity of energy reducing technologies can be formalized in a model and expedited with directed policies.

Methodology Overview

The research first draws on literature review to select the three most promising carbon intensity of energy reducing technologies for the case of the Port of Rotterdam. The technologies are assessed according to several factors, for which semi-structured interviews with technology experts provided more insights into the most relevant barriers for adoption. These insights were then formalized in a system dynamics model created in Vensim, for which the structure and behaviour was validated with expert interviews. The model captures important feedback mechanisms between truck adoption, charging infrastructure supply, technology maturity and awareness, and total cost of ownership. On these feedback mechanisms, policy interventions available to the Port of Rotterdam Authority have been tested. Lastly, scenario analysis for container volume throughput has been performed to assess system robustness and identify key drivers of uncertainty.

Key Insights

The study identifies five conditions for effective adoption of carbon intensity of energy reducing technologies:

- **Availability of charging infrastructure**, influenced by market supply conditions and planning and construction delays
- **Technology maturity**, measured as performance and reliability of a technology and backed by R&D investments from sales
- **Technology awareness**, measured as percentage of the truck fleet of that specific technology type
- **Energy source availability**, an important driver for initializing truck decarbonization at energy hubs
- **Lifecycle costs including energy efficiency**, calculated per year to guide investment decisions from trucking companies

These factors are interdependent, tied together through feedback loops and delays. Since no large model sensitivities in the model were possible to target for the Port of Rotterdam Authority, the feedback loops have been the base for identifying effective policy interventions. Two policy interventions played an especially effective role in targeting exponential growth of adoption:

- **Lower-emission truck adoption rate stimulation**, increasing relative attractiveness of lower-emission trucks.
- **Collaborative BET-implementation project**, stimulating early adoption of BETs by bringing together stakeholders.

Both policy interventions leveraged feedback loops, reducing the problems experienced in the early growth phase of technologies and initializing the exponential growth phase of adoption. Lower-emission truck adoption rate stimulation did so more effectively, due to its possibility to be implemented at an earlier stage.

Conclusion

This study shows how the Port of Rotterdam's switch from diesel to lower-emission trucks depends on the interaction of governmental backing, infrastructure construction, and technology maturity. While Fuel-Cell Electric Trucks may be used for long-distance applications if hydrogen infrastructure is developed and green hydrogen becomes cheaper, Battery Electric Trucks exhibit greater medium-term potential due to their quicker cost reductions and increased efficiency.

Actionable Recommendations

For the Port of Rotterdam Authority, three recommendations are suggested. First, implement policy interventions as soon as possible. This will hasten adoption by removing obstacles related to infrastructure and awareness, and the effects will compound over time. Second, since the Port of Rotterdam Authority's narrow mandate is insufficient to achieve significant reductions on its own, coordinate efforts with national strategies. The developed model can help guide more general government policies. Third, give preference to Battery Electric Trucks, which perform better than Fuel-Cell Electric Trucks in terms of cost, maturity, responsiveness of the infrastructure and emission reduction.

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List of Abbreviations

BET	Battery Electric Truck.
CAPEX	Capital Expenditures.
CCS	Carbon Capture and Storage.
CCU	Carbon Capture and Utilization.
EC	European Commission.
EPA	Engineering and Policy Analysis.
ETS	Emissions Trading System.
EU	European Union.
FBL	Feedback Loop.
FCET	Fuel-Cell Electric Truck.
GDP	Gross Domestic Product.
Gtkm	Giga tonne-kilometres.
GW	Giga-Watt.
ICE	Internal Combustion Engine.
km	Kilometres.
KPI	Key Performance Indicator.
kW	Kilo-Watt.
kWh	Kilo-Watt-Hour.
LCOE	Levelized Cost Of Electricity.
Mt	Mega tonnes.
Mtkm	Mega tonne-kilometres.
MW	Mega-Watt.
OPEX	Operational Expenditures.
P2G	Power-to-Gas.
P2L	Power-to-Liquid.
PoR	Port of Rotterdam.
PoRA	Port of Rotterdam Authority.
RED	Renewable Energy Directive.
SD	System Dynamics.
TCO	Total Cost Of Operation.

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1

Introduction

With a cargo throughput of about 436 Mega tonnes (Mt) of freight a year, the Port of Rotterdam (PoR) is the largest port in Europe (Port of Rotterdam, n.d.-a). The port creates employability for about 500,000 employees and adds roughly €60 billion to the economy of the Netherlands (Port of Rotterdam, n.d.-a). When compared to the total Gross Domestic Product (GDP) of The Netherlands of 1.15 trillion (World Bank, n.d.), this added value to the economy equals to approximately 5.2% of total GDP in The Netherlands. Given the historic position of The Netherlands as one of the largest of the group of small countries, it is vital for the future of the country to maintain this strong catalyst for trade in the country.

Besides being a port with a very large throughput, the Port of Rotterdam is also part of a Dutch port infrastructure that is internationally lauded. Due to the extensive hinterland transport, major investment projects in the region and its state of the arts facilities, the Port of Rotterdam has contributed greatly to this receipt of the prize for best port infrastructure by the World Economic Forum several times. But even this established well-functioning port infrastructure is constantly reviewed, while research occurs for new improvements.

An important area for improvement is the decarbonization of the Port of Rotterdam towards an emission-free port in 2050 in alignment with the European Green Deal that seeks to obtain the goals of the Paris Agreement by reaching a climate-neutral European Union (EU) by 2050 (European Commission, 2018). The Port of Rotterdam is responsible for 21.5 Mt of the total CO₂-emissions of The Netherlands of 118.67 Mt (Ritchie et al., 2024). Specifically, hinterland transport, which encompasses the transport of imported cargo from the Port of Rotterdam towards their end destination, as well as cargo from its origin in the hinterland that is exported through the Port of Rotterdam. With 2.22 Mt of CO₂-emissions, hinterland transport is responsible for 9% of total Port of Rotterdam CO₂-emissions (Lechtenböhmer et al., 2018). Hinterland transport encompasses multiple modes of transport – road traffic, rail traffic and inland waterway – among which the pathway of road traffic bears the most potential for CO₂-emissions reduction.

In 2017, road transport by trucks accounted for 58% of the modal split of hinterland transport for the Port of Rotterdam (Binnenvaartcijfers, 2017), while it has remained relatively stable with 55% in 2023 (Port of Rotterdam, 2024). This modal split does not tell the whole story, since truck transport accounts for only 20% of this hinterland transport volume in Giga tonne-kilometres (Gtkm) from the Port of Rotterdam (Lechtenböhmer et al., 2018), due to the mostly short trips in hinterland transport that are executed by truck. However, this relatively small percentage of transport volume does produce 0.9 Mt in CO₂-emissions and thereby leads to 40% of the total CO₂-emissions of hinterland transport, as can be seen in Figure 1.1.

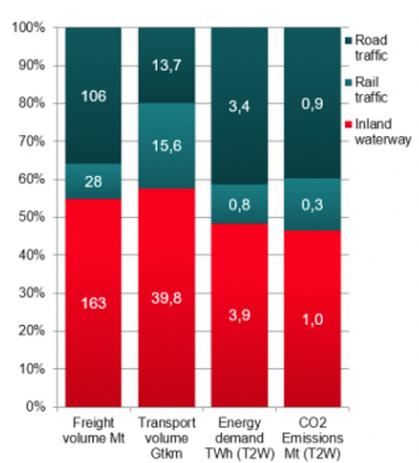


Figure 1.1: Transport volume and corresponding CO₂-emissions for PoR hinterland transport modalities (Lechtenböhmer et al., 2018)

With liquid and dry bulk cargo expected to be significantly reduced by 2050 due to less need for these goods in a decarbonized economy, it is expected that container transport will become the dominant cargo modality in hinterland transport (Lechtenböhmer et al., 2018). As can be seen in Figure 1.2, it is expected that container transport in this timeframe will increase by roughly half from 140 Mt to 212 Mt (Lechtenböhmer et al., 2018). Given that about a third of container transport is done by diesel truck, this more polluting form of hinterland transport of truck transport will contribute more significantly to the carbon emissions of the Port of Rotterdam.

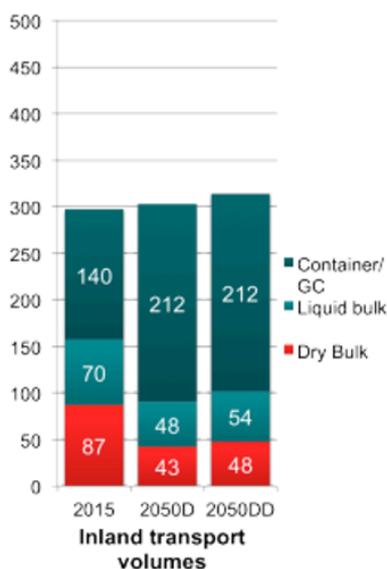


Figure 1.2: Hinterland transport volume prediction for 2050 (Lechtenböhmer et al., 2018)

The system of hinterland truck transport is complex since it shows characteristics of a wicked problem, as defined by Rittel & Weber (Rittel & Webber, 1973). The system of hinterland truck transport is influenced by multiple actors with occasional conflict on values. For example, a trucking company transporting containers in the Port of Rotterdam is more focused on the transport price for its operation, while the Port of Rotterdam Authority (PoRA) dedicates less value to the transport price when it comes at the cost of more CO₂-emissions. Another aspect of wicked problems is that there is uncertainty about available objective information (Rittel & Webber, 1973). Various low-carbon intensive technologies are proposed in literature (Lechtenböhmer et al., 2018) but it is unsure how these technologies compare

and may complement each other. Technology adoption requires longer-term investments and various trade-offs that must be calculated for the medium-term. Multiple medium-term fleet centred models exist, but among them system dynamics (SD) was chosen as a method due to the dynamic mechanisms at play in the truck hinterland transport system. Successful adoption of the lower carbon intensity of energy technologies requires the presence of multiple factors like charging infrastructure, presence of required energy sources and complementarity with hinterland transport routines. These factors are interdependent and must therefore be studied jointly. In order to include all factors at stake for carbon intensity of energy reduction technology adoption, a high level of aggregation has been chosen. Studying the highly relevant interdependencies between the sub-systems has been preferred over more depth in the sub-systems. Interdependencies between factors are also characterized by dynamic processes such as feedback loops (FBLs) and delays. To effectively estimate the projected future value of systems, predict whether time-horizon objectives can be realized, comprehend the rate of system changes, and enable the realignment of investments and policies with the status quo, assumptions about dynamics are required (Tavasszy, 2020). During this medium-term timeframe, feedback loops - investments and their effect on maturity, the influence of sustainability on transport costs, influence of adoption on charging infrastructure built – will play their part. Also, delays for truck adoption, charging infrastructure construction and price elasticity can hamper the steering of system behaviour towards a decarbonized future. Given that dynamic mechanisms such as feedback loops are exacerbated when considered for this medium-term timeframe, it is essential to include them in a system dynamics model to calculate valid values for the KPIs that can truly aid the Port of Rotterdam in obtaining its CO₂-reduction goals for 2050.

The internal interactions in system dynamics models are based on mathematical integral equations that update the state of the model according to a chosen timestep. However, the initial values and constants that are at the foundation of these mathematical equations differ based on the specific energy hub environment, which entails that a specific case study is required to gather tangible outcomes. The case study method provides an analytical framework for examining the complex sociotechnical system of truck hinterland transport within a real-world context. Therefore, the Port of Rotterdam has been chosen as a concrete case study. Each port has its own specific characteristics – trading balance, distance to customers – that can lead to different pathways to decarbonized truck supply chains. The adoption of lower carbon intensity of energy technologies is heavily influenced by future trade volumes, that for the concrete example of the Port of Rotterdam can be captured in designed scenarios. With these numbers in hand, a well-balanced strategy can be defined for obtaining the Port of Rotterdam decarbonization goals. In order to do so, the chosen technological innovations must align with the energy and cargo streams that pass through the Port of Rotterdam, thereby not endangering its position as preferred port for many industries and the largest port in Europe. By studying these relevant adoption factors in unison, the knowledge gap can be adequately addressed and sensitivities can be traced in the model that form the pressure points to aim at for policy interventions that can effectively speed up adoption of low-carbon intensive technologies. The results will have spillover effects to other ports and other kinds of energy hubs with similar energy streams present.

The following central research question guides this research:

”What is the most viable technology for the reduction of the carbon intensity of energy for trucks involved in the dynamic hinterland transport of the Port of Rotterdam?”

In order to address this research question, this thesis is structured as follows. The pertinent literature is reviewed and the resulting knowledge gap described in Chapter 2. The research design, including the central research question, supporting questions, and selected methodologies, is described in Chapter 3. The technological options under consideration are presented in Chapter 4. The System Dynamics model and its sub-models are developed in Chapter 5. The model is used in Chapter 6 to assess the effects of policy interventions. The results, restrictions, and wider ramifications are covered in Chapter 7. Finally, Chapter 8 concludes by answering the research questions and providing recommendations for practice and future research.

2

Literature Review

In this chapter a literature review is performed in the first four sections for research fields that are closely related to the problem described in the introduction. The search strategy behind this literature review, as well as the motivation for the division into four rounds is described in Appendix A. In the last section, a knowledge gap is distilled from the results of this literature review that forms the motivation for this specific research.

2.1. Increasing importance of truck hinterland transport in the Port of Rotterdam

Transporting commodities from the port to inland locations and from inland locations to the port is known as hinterland transport, and it is an essential part of the port's entire logistics chain. Approximately 75% of worldwide trade is supported by ports, which play a unique role as links between land and marine freight (Lind et al., 2023). The majority of research focuses on decarbonizing maritime transportation and in-port operations, despite the fact that hinterland transportation makes up the other half of this intermodal hub and contributes significantly to port-related emissions (Alzahrani et al., 2021). The hinterland has frequently been neglected in port energy transition initiatives, which have so far mostly focused on efforts at sea (Bjerkan et al., 2021). Only 76 out of 365 ports presently employ initiatives addressing hinterland decarbonization, according to a survey of academic literature and green port plans, indicating that the potential influence of ports in decreasing hinterland transport emissions has received little attention (Gonzalez Aregall et al., 2018). Port of Rotterdam is one of these 76 ports at the forefront of hinterland transport decarbonization, as it should to reach its goal of being a climate-neutral port by 2050. Truck transportation is the most carbon-intensive mode of transportation per tonne-kilometer and is predicted to gain modal share over the next several decades (Lechtenböhmer et al., 2018). As a result, this study specifically focuses on truck transportation due to its increasing importance and substantial emissions impact.

The truck hinterland destinations and origins result in different routes. 40% of total journeys are to/from the Rotterdam region, 50% to/from other parts of The Netherlands and 10% are to/from locations abroad (Port of Rotterdam, n.d.-b). It could not be retrieved from sources whether this division is different for hinterland locations that use the Port of Rotterdam as an importing or exporting port. The most recent indication of Port of Rotterdam hinterland volumes from 2015 indicate that truck hinterland transport consists of 106 Mt of cargo (Lechtenböhmer et al., 2018). With a relatively short average transportation distance of 129 kilometres (km) this truck hinterland transport encompasses a total of 13.7 Gtkm (Lechtenböhmer et al., 2018). When this cargo flow grows as expected, absolute emissions from truck hinterland transport rise, making the contribution of truck hinterland transport to the port's overall goal of becoming a carbon-neutral port by 2050 a more negative one. Therefore, it is important to consider simulations based on future cargo flows when calculating the future carbon-emissions from truck hinterland transport.

Although simulations of future cargo flows often have a subjective character, basing their assumptions on expert opinions, they can also be more evidence-based and aid in future planning for port development. On the one hand, short-term simulations of trucking traffic can aid in determination of the short-term traffic flow surrounding the port. For the port of Rotterdam this has been done by using the Port Community Systems and truck count data as inputs for an Artificial Neural Network (Nadi et al.,

2021). However, for the longer-term investments required for the decarbonization of truck hinterland transport, insights covering a longer timespan are required. Organisations like the Wuppertal Institute have made such predictions specifically for the port of Rotterdam. Basing the predictions on reports from organisations like the IEA, EC and WWF they have constructed two relatively climate-positive scenarios for 2050 (Lechtenböhmer et al., 2018). In these scenarios, there is less demand for dry and wet bulk goods that are currently used in polluting industrial processes, such as coal, iron ore and crude oil. Dry and wet bulk goods are dominantly distributed in the hinterland by train or waterway. Meanwhile, the demand for container transport, mostly done with trucks, is expected to increase by about 50% (Lechtenböhmer et al., 2018). Four scenarios for 2050 based on global political developments from the Port of Rotterdam itself describe this same transition towards more container transport volumes and therefore increased use of the truck modality for Hinterland transport (Port of Rotterdam Authority, 2021). This creates urgency to think about the carbon emission of trucks as a vital part of the hinterland transport for the port of Rotterdam of the future. Also more recently, the Port of Rotterdam Authority has made an estimation of four global political scenarios and how these influence the throughput of the Port of Rotterdam over the years: Connected Deep Green, Regional Well-Being, Protective Markets and Wake-Up Call (Port of Rotterdam Authority, 2021).

2.2. Technological advancement towards a future of less carbon intensive truck transport

The study's scope is restricted to the technological substitution of carbon-intensive energy sources used by trucks that are part of truck hinterland transport. Other decarbonization strategies like boosting load factors, improving fleet energy efficiency or optimizing routing are not taken into account; these are also means to the same goal but outside the scope of this research (McKinnon, 2018). A more thorough examination of technology alternatives including electricity-based propulsion, hydrogen-based propulsion, and alternative low-carbon e-diesel is made possible by this focused approach.

2.2.1. Internal combustion engines

Currently, port of Rotterdam hinterland truck transport leads to 65.7 grammes of CO₂-emission per kilometer of transport of one tonne of goods (g/tkm), including a correction for partial load of the trucks (Lechtenböhmer et al., 2018). This high level of pollution is due to the high carbon intensity of energy of diesel that is used in the internal combustion engines (ICEs) that are driving 97% of the Dutch truck fleet (European Automobile Manufacturers' Association (ACEA), 2025). In the current state, hinterland truck transport is much more polluting than its alternatives for hinterland transport, rail transport (19.2 g/tkm) and inland ship navigation (25.1 g/tkm) (Lechtenböhmer et al., 2018). However, it does produce more flexibility because trucks do not depend on static distribution channels as much as waterways and rail lines, which creates shorter delivery routes especially for short distances (Zhang & Pel, 2016).

2.2.2. Technologies for reduction of carbon intensity of energy

In order to reduce the emissions from the hinterland truck transport, one category of solutions focuses on reducing the carbon intensity of energy for trucks (McKinnon, 2018). For the port of Rotterdam, three main categories of reducing the carbon intensity for road trucking transport – the use of e-diesels produced by CCU, Battery Electric Trucks and Fuel-Cell Electric Trucks - have been identified (Lechtenböhmer et al., 2018).

First of all, two forms of carbon capture and utilization (CCU) are options as direct fuel-alternatives for the combustion engines of current trucks. These CCU-technologies incorporate the capture step from Carbon Capture and Storage technologies (CCS), but instead of storing also use the captured CO₂ as a building block for the production of high-value hydrocarbons through a process called hydrogenation (Gao et al., 2021). Power-to-liquids (P2L) and power-to-gas (P2G) are two well-established CCU methods that are two examples of viable alternatives for the port of Rotterdam (Lechtenböhmer et al., 2018). In comparison to P2G, P2L technology can be viewed as more mature due to its higher energy density, added value, ease of transportation and transportation (Gao et al., 2021). Indirect P2L - in which intermediary products such as methanol and syngas are produced - are characterized by their flexibility, modularity and maturity, giving them a competitive edge over direct P2L processes (Saric et al.,

2021). In order to compare the most viable technological version of the different subcategories of carbon intensity lowering technologies, indirect P2L is the only form of CCU that is considered in this study. Additionally, CCU does need green hydrogen in order to be a sustainable alternative, which requires a large water electrolysis unit running on renewable energy. This infrastructure would have to be present in the ecosystem of the port of Rotterdam or the green hydrogen would have to be imported from abroad.

Secondly, a larger system transition would be required when the carbon intensity of the energy is reduced by replacing the ICEs in the trucks used by involved transport companies for more sustainable alternatives. Out of these technologies, the technology with the lowest cost of ownership is the introduction of battery electric trucks (BETs) (Noll et al., 2022). However, it would require charging stations that BETs could use during their long charging time, while BETs are especially economical for short distances within the urban region of Rotterdam (Noll et al., 2022).

Lastly, another promising option consists of replacing trucks by Fuel-Cell Electric Trucks (FCETs) that drive solely on hydrogen, which renders a lower carbon intensity of energy used (Lechtenböhmer et al., 2018). Since both FCETs and BETs are powered by electric motors, they function similarly. But unlike BETs, FCETs get their power from a hydrogen fuel cell, which powers the electric motor. Electrochemical devices known as hydrogen fuel cells use hydrogen's chemical energy to produce heat, electricity, and water. Advantages of this technology are that the FCETs require little stationary time when refilling the hydrogen, as well as not overburdening pressurized electricity grids (Cunanan et al., 2021). Another advantage of FCETs is their zero tailpipe emissions, because there is no need for combustion to produce usable energy. There are various types of fuel-cells that can drive FCETs including the proton exchange membrane fuel cell (PEMFC), alkaline (AFC), phosphoric acid (PAFC), solid oxide (SOFC), molten carbonate (MCFC), and more (Cunanan et al., 2021). From these, PEMFC is regarded the most promising fuel-cell technology option in literature, due to its automatic control (Dalvi & Guay, 2009), portability (Aminudin et al., 2023) and optimum operating points and its capability to start in low-temperature conditions (Granovskii et al., 2006). For typical PEMFC, the hydrogen atoms from the fuel tank are ionized at the anode (Fuel Cell & Hydrogen Energy Association, 2021). Following their passage through the proton exchange membrane, the hydrogen protons react with oxygen to produce water as a byproduct. In the meantime, the vehicle's electric motors or battery can be charged using the electrons that were extracted from the hydrogen fuel.

2.3. Decarbonization of truck transport specifically at energy hubs

This subpart of the literature synthesis aimed to investigate the role of energy hubs – such as ports – in the decarbonization of truck transport. In the search strategy for this subpart, it turned out that there is little research combining trucks and energy hubs. Specifically for ports the research is generally more focused on the opportunities for greener truck transport, without elaborating on how the energy sources present in the ports can aid in this (Jiang et al., 2025; Song, 2021).

As alternatives for combustion trucks require the production of green hydrogen and electricity, as well as the storage of CO₂, the energy sources that run through the port of Rotterdam can play a vital role in setting up efficient delivery processes for these energy sources. The Port Authority can fulfill the role of facilitator of renewable energy, as has been showcased in the ports of Hamburg and Genoa (Acciaro et al., 2014). As ports are not energy companies, there is a need to collaborate with local energy companies (The Maritime Executive, 2020). For example, ports possess privileged access to offshore wind and can use this renewable wind energy to power BETs or produce hydrogen with (Eurelectric, 2024). Ports can also serve as natural conduits for integrating offshore wind into the power system, which helps to alleviate the grid balancing challenge of wind energy. By allowing the export of renewable energy to adjacent industry clusters or for electrified highways, rivers, and short-distance sea transportation, ports can assist in balancing the distribution grid in the event that wind capacity surpasses the host capacity. This prevents curtailment and provides a cost-effective substitute for storage in addition to facilitating the integration of renewable energy sources. (Eurelectric, 2024). Four scenarios have been developed that display different decarbonization strategies for the Port of Rotterdam ecosystem and the renewable energy streams that accompany these different decarbonization paths (Samadi et al., 2018).

2.4. System dynamics as an analytical tool for exploring uncertainty of sustainable truck implementation

System Dynamics is a modeling methodology rooted in systems thinking, designed to analyze and simulate the dynamic behaviour of complex systems over time (Pruyt, 2013). In order to do so it is able to capture feedback loops, delays and interdependencies (Auping et al., 2012). Within this research, SD offers valuable insights into medium-term planning for policy interventions and the resulting values of key performance indicators (KPIs) for the port such as CO₂-emissions. SD also possesses the ability to analyze feedback mechanisms and policy impacts within energy systems, facilitating a deeper understanding of electricity sector outcomes (Ahmad et al., 2016). Similar uses of SD for port hinterland transport can be found for the ports in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) (Zhong et al., 2023), where SD has been utilized to assess the long-term impacts of carbon taxation policies. Although targeting a different environmental policy concerning less infrastructural interventions, it does show insights into the intricacies of a large port system and the actors required to establish systemic change. For the port of Shanghai SD has been utilized to investigate port congestion (Xu et al., 2021). Also, for the port of Shanghai SD has been used to investigate the introduction of new technologies to hinterland transport, as part of a larger research into increasing port sustainability, without specifically focusing on reduction of carbon intensity of energy for trucks (Hou & Geerlings, 2016). For the Brazilian transport system SD has been used similarly to investigate policies for decarbonization in ports, with some of the policies researched focusing on reducing the carbon intensity of energy for trucks (Ghisolfi et al., 2024). For the Caofeidian port relevant hinterland transport emission subsystems have been created, while taking into account different intervening policies, but without taking investment costs into consideration (Liu et al., 2019).

2.5. Knowledge gap

As shown in the state of the art, truck hinterland transport is the most CO₂-emitting and also most rapidly growing modality of the hinterland transport modalities. Therefore, multiple strategies for decarbonisation of truck hinterland transport have been researched in literature. However, these technologies focusing on reduction of carbon intensity of energy have always been researched in combination with other types of technologies, instead of focusing solely on carbon intensity of energy reduction technologies. For this research, three specific higher-maturity carbon intensity of energy reduction technologies have been identified, that have the potential to facilitate the transition to a carbon-neutral Port of Rotterdam by 2050. In order to discover how the adoption of these technologies can be expedited by targeted policy interventions, it is important to know how these technologies perform on key performance indicators such as transport price per Mega tonne-kilometre (Mtkm) and CO₂-emission reduction in the medium-term. By using system dynamics as a method important dynamic processes involved with the adoption of lower carbon intensity of energy technologies are captured. Feedback loops that mitigate or intensify involved causal effects, especially in the medium-term, can be built in. The truck hinterland transport system under analysis should also include the availability of energy sources and charging infrastructure, as these factors can expedite or hamper to adoption of technologies that reduce the carbon intensity of energy of trucks. System dynamics is able to show the interdependencies between these different factors for success. It can elegantly implement delays involved with the construction of new charging infrastructure or portray market effects, helping with the correct timing of policy interventions in the system of truck hinterland transport.

The following research question is aimed at addressing this knowledge gap and guides this study:

”What is the most viable policy intervention for the reduction of the carbon intensity of energy for trucks involved in the dynamic hinterland transport of the port of Rotterdam?”

3

Research approach

In this chapter the approach to answering the research question is explained. In the first section, the central research question is further elaborated on. In order to answer this central research question, it is necessary to follow consecutive steps guided by the sub-questions. The methods utilized to generate the answers to these sub-questions are explained in the second section. In the last section, it is explained how the coherence of these methods leads to an answer to the main research question.

3.1. Research questions

In order to contribute to research specifically into the adoption of carbon intensity of energy reduction technologies, for which the dynamics at play can be studied in detail by looking at a specific case study of an energy hub like the Port of Rotterdam, the following research question guides this study:

”What is the most viable technology for the reduction of the carbon intensity of energy for trucks involved in the dynamic hinterland transport of the Port of Rotterdam?”

The main objective from answering this question is to provide an evidence-based answer to which technological interventions are preferred in the specific energy hub example of the Port of Rotterdam, in order to reach the 2050 climate goals for truck hinterland transport as efficiently as possible. A technological intervention is viable when it scores sufficiently across a range of key performance indicators that are defined for the Port of Rotterdam Authority. The key performance indicators are identified for the Port of Rotterdam Authority, since this problem owner is in the best position to decide which trade-off of KPIs is best for the future of the Port of Rotterdam ecosystem as a whole. The key performance indicators take into account the sociotechnical nature of the truck hinterland transport system, as well as the public ownership of the Port of Rotterdam Authority in the hands of the municipality of Rotterdam (70,83%) and the Ministry of Finance of The Netherlands (29,17%) (Ahlers et al., 2020). The key performance indicators are: Total CO₂ emissions of the hinterland truck transport, Adoption rate, Transport price per Mtkm and charging infrastructure available. The three sub-questions are the following:

1. Descriptive:

- Which technologies for reduction of carbon intensity of energy for trucks align with the position of the Port of Rotterdam as energy hub?

2. Application of system dynamics:

- How can the relevant dynamic factors for transition to lower carbon intensive energy for truck hinterland transport of the Port of Rotterdam be formalized in a System Dynamics model?

3. Application of system dynamics:

- How can policy interventions by the Port of Rotterdam Authority expedite the transition towards lower-emission trucks before 2050?

The sub-questions are designed to address both academic and practical dimensions of the research, aligning with the Engineering and Policy Analysis (EPA) evaluation criteria. The study engages directly with a grand societal challenge— sustainable truck transport — and examines the complex interplay between port authorities, trucking companies and charging infrastructure providers.

3.2. Research methods

This research utilizes a mixed-methods approach, consisting of qualitative and quantitative methods to discover the systemic impacts of carbon intensity of energy for trucks reducing technologies in the medium-term (Swanson & Holton, 2005). The quantitative method consists of a system dynamics model with a high level of aggregation, that can calculate medium-term scenarios and dynamics for the adoption of multiple technologies in hinterland truck transport of the Port of Rotterdam. The qualitative part consists of multiple methods, semi-structured interviews and literature research. The additional use of AI has been described in Appendix F. A detailed research flow diagram, containing an overview of the different methods and the phases during which these are utilized, can be found in Figure 3.1. The use of these methods is discussed in relation to the sub-questions they aid in answering in the following sub-sections.

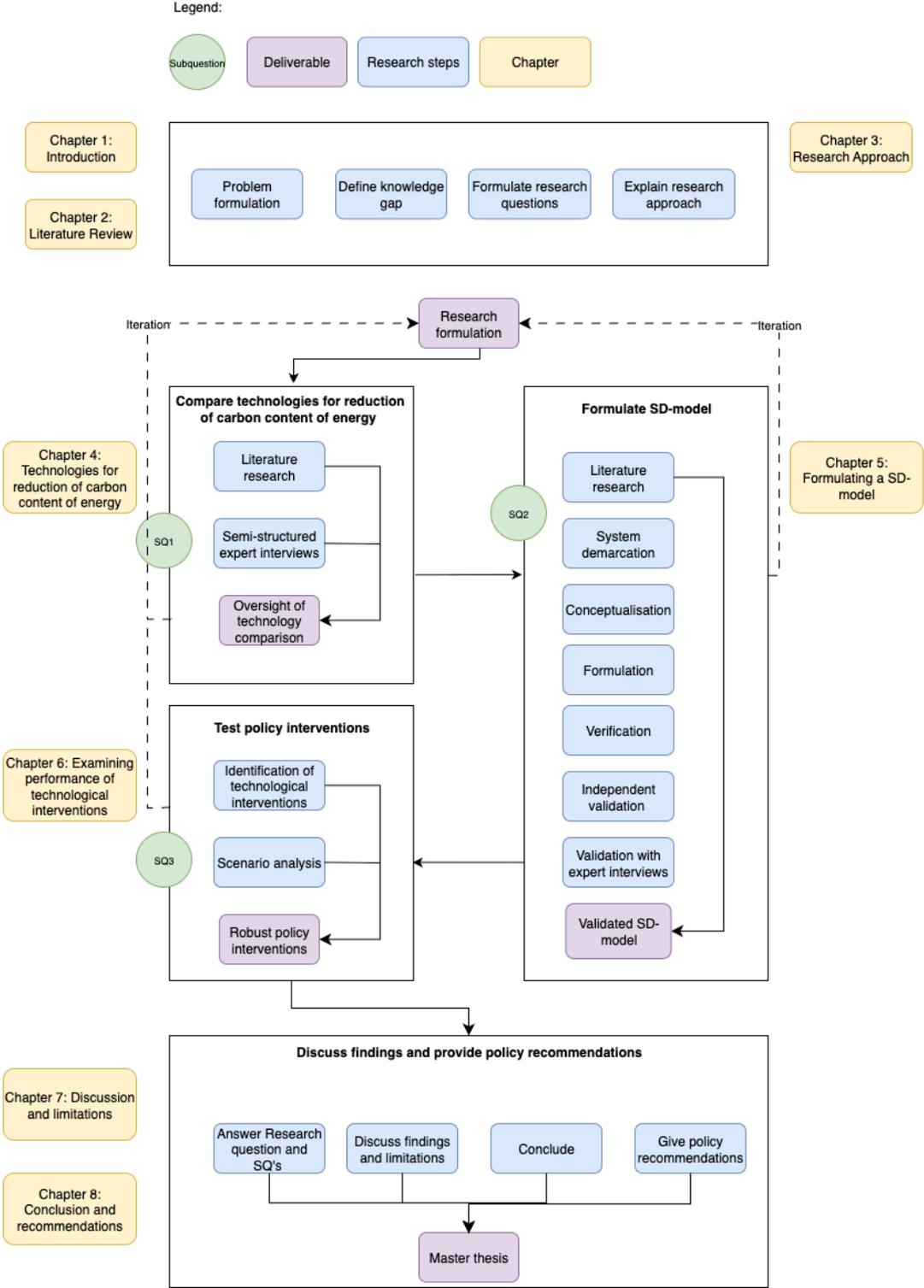


Figure 3.1: Research flow diagram

3.2.1. Methodological approach for describing alignment of technologies with the Port of Rotterdam hinterland transport

For the answering of sub-question 1, first semi-structured interviews have been used to define structural boundaries for the collection of information, followed by directed literature research to collect this information.

Semi-structured interviews

Interviews were used to gather insights into the technologies for reduction of carbon intensity of energy, required for the answering of sub-question 1. Interviewing is a versatile method for understanding complex social phenomena across various study topics. The interviews have formed an excellent mean for providing information and deepening understanding (Guest et al., 2013), which was required at the initial stages of this research to guide the further study. The three interviews with experts from these fields have provided relevant insights into which elements of the technology are vital for its further adoption in the real world, which has influenced the identification of relevant barriers for technology adoption that have become the sub-sections of Chapter 4. Furthermore, the experts could provide practical insights from working with these technologies that were not present in literature. Information about the background and expertise of experts is provided in Table 3.1

Expert	University researcher	Applied researcher	Port executive	Area of expertise
Expert 1	X			BETs
Expert 2	X			FCETs
Expert 3		X		E-diesel

Table 3.1: Expert overview by affiliation for first round of interviews

For the interviews, a semi-structured style was chosen in order to maintain more flexibility and gather more in depth data from the interviewees (Adeoye-Olatunde & Olenik, 2021). All of the interviews were guided by only a robust interview questionnaire, that varied per respondent based on the specifics of their field of expertise. These different questionnaires created the initial structure for the interviews but also allowed for the exploration of emerging themes based on the relevance that the interviewee attributed to specific themes. For the interviews, adherence to ethical guidelines and use of reflexivity is described in Appendix B.

Literature research

The second qualitative method utilized for the answering of sub-question 1 was literature research. This literature research encompassed a deep dive into reports recommended by the experts during the interviews and those that stood out during the literature review of background information. Information gathered from these sources was used to provide an overview of the relevant knowledge about adoption factors, that had arisen from the interviews. Given the novelty of a topic like reduction of carbon intensity of energy for trucks, many up-to-date sources exist. Technological development is fast in the research area of carbon intensity of trucks, which is why literature from after 2020 was preferred to avoid basing research assumptions on outdated sources.

3.2.2. Methodological approach for formalizing the relevant dynamic factors in a system dynamics model

For the answering of sub-question 2, the modelling cycle prescribed for the use of system dynamics has been followed. This modelling cycle was backed by vital inputs from the qualitative methods of interviews and literature research.

System dynamics

Systems thinking is a theoretical anchor that aims to grasp entire systems and their internal interactions instead of isolating components separately, which is a suitable approach for studying complex dynamic systems (Ramage & Shipp, 2009). In particular, freight transport modeling can be used to investigate novel structural components of the freight transport system, such as those found in adjacent systems like energy and climate (Tavasszy, 2020). In the next sub-sections it is explained what elements of the

truck hinterland transport have led to the choice of system dynamics as the preferred system modelling method.

Given that the CO₂-reduction goals of the Port of Rotterdam are set for 2050, the timespan for the model is up until 2050 and covers 25 years, which classifies as medium-term for freight transport modelling. This medium-term classification is used for freight transport modelling for a modelling timeframe of 10 to 40 years (Tavasszy et al., 2023). By choosing this timeframe, the model can account for dynamics of strategic and tactical logistics decisions such as adoption of lower carbon intensity of energy technologies. Also, responses to structural changes in demand and supply through price elasticity can not be measured in the short-term but are possible to model with this medium-term timeframe (Tavasszy et al., 2023). Furthermore, in comparison to long-term modelling techniques it is not possible to model changes in institutions, cultures or regime (Tavasszy et al., 2023). However, this appears not necessary with the Port of Rotterdam Authority firmly in charge as facilitator of port trade, with no changes in other port actors expected. Lastly, according to this classification of the medium-term in literature it is not possible to model changes in physical infrastructure (Tavasszy et al., 2023). However, given the short construction time of charging stations of 2 years according to (REEL, 2022) and the exclusion of longer-term infrastructural construction times for grid capacity expansion or energy generation infrastructure, it was decided to include changes in charging infrastructure in the model.

For this medium-term model a fleet-centred approach has been chosen. The fleet-centred approach is fundamentally based on stocks of vehicles, technical capital, or demand distributed over different modes (Tavasszy et al., 2023). This aligns with the context of the hinterland truck transport system, where different truck types and charging stations can be displayed as stocks and demand is distributed over these competing truck types. Also, a fleet-centred model allows for the calculation of new technology adoption and corresponding KPIs based on endogenous system states to study the dynamics of the system instead of inserting sets of estimations (Tavasszy et al., 2023). The velocity of medium-term dynamics is based on the rate of change of physical capital and the rate of change of behaviour of the actors (Tavasszy et al., 2023). In this research, the physical capital consists of the different truck types and charging stations. The behavioural change modelled is that of the choice of trucking companies to adopt the lower carbon intensity of energy technologies, as well as that of charging infrastructure providers to construct charging stations.

The case study method applied to the Port of Rotterdam provides an analytical framework for examining the complex sociotechnical system of truck hinterland transport within a real-world context. As defined by Yin (Yin, 2009), a case study is 'an empirical investigation that examines a contemporary phenomenon (the "case") in depth and within its real-world context'. In order to include all of the sub-models at stake for carbon intensity of energy reduction technology adoption, a high level of aggregation has been chosen. Studying the highly relevant interdependencies between the sub-systems has been preferred over more depth in the sub-systems. In order to reach the depth in the sub-models that is required to replicate real-life behaviour, sub-models have been based on existing system dynamics models if such an example existed. When such a model was used as inspiration for a sub-model in this study, great care was administered to ensure that these models were adapted to the local environment of the Port of Rotterdam.

For the answering of sub-question 2, the first four of five consecutive steps of the modelling cycle are performed: Problem articulation, conceptualisation, formulation and evaluation. The first step, problem articulation, is necessary to scope the aggregated system of truck hinterland transport for the Port of Rotterdam concretely. Problem articulation encompasses the definition of system boundaries and the motivation for why system dynamics is fit for finding answers to the research questions. In the second step of conceptualisation, the system is divided into sub-systems that play a part in the transition to lower carbon intensity energy; adoption of lower-emission trucks, energy supply in the port, charging infrastructure and truck transport. These sub-systems and their internal relations stem from literature research. Sub-systems such as charging infrastructure and energy supply in the port are adapted to the specific technologies that are selected after answering sub-question 1. Then, important feedback mechanisms and delays from literature are explained in relation to the case. Lastly, KPI's for the system can be appointed. Then, in the second step the conceptual model can be formalized by translating them

to mathematical terms suitable for a System Dynamics model. The third step of the modelling cycle consists of the evaluation of the model by means of verification and validation. Verification will be done by ensuring that there is dimensional consistency and no other mathematical errors occur in the model. The evaluative step of validation is twofold: first, validation will be done independently through extreme values tests and sensitivity analysis, after which validation will be performed on the basis of expert interviews.

These modelling steps are common to the Delft method for system dynamics, but also to other system dynamics methods such as the original method for system dynamics as developed by Forrester at MIT. What sets the Delft method for system dynamics apart is the focus on communication and reporting of the results (Meyers et al., 2010). This focus encourages the modeller to look past the modelling practice and evaluate the effects of using the model to guide policy (Meyers et al., 2010). That way, the modeller could actively engage in societal debate by showing the trade-offs among KPIs that are relevant to port actors. This engaging approach is also a prerequisite for providing a valuable contribution to the grand societal challenges posed by the sociotechnical systems studied in the Engineering and Policy Analysis curriculum.

Literature research

Literature research has delivered quantitative data from numerous sources in order to be used for the system dynamics model. When specific relations were absent, for example for feedback from transport dynamics with energy flows due to it being an under researched topic, assumptions in conclave with experts have been made in order to create a complete model. Sensitivity analysis formed an extra mechanism to address these uncertainties in the data.

Interviews

Expert interviews have been used for the validation of the system dynamics model to ensure its strict adherence to the real-world situation in the Port of Rotterdam (Pruyt, 2013). For the interviews, adherence to ethical guidelines and use of reflexivity is described in Appendix B. The interviewees from four interviews have been asked to perform three tests relevant for validation: surprise-behaviour test, behaviour-prediction test and behaviour-reproduction test (Auping et al., 2024). With these test it could be assessed whether the model is fit for purpose and can be trusted enough to base policy interventions for hinterland truck transport on (Forrester & Senge, 1980). The interview questions that the interviewees were asked can be found in Appendix D.2.1-D.2.3. Information about the background and expertise of experts is provided in Table 3.2.

Expert	University researcher	Applied researcher	Port executive	Area of expertise
Expert 4			X	Sustainable mobility in ports
Expert 5		X		Port and hinterland logistics
Expert 6	X			BET adoption
Expert 7	X			BET adoption

Table 3.2: Expert overview by affiliation for second round of interviews

3.2.3. Methodological approach for testing policy interventions to expedite the transition towards lower-emission trucks

For the answering of sub-question 3, the last step of the modelling cycle is performed: Policy testing. When the SD-model was operational, it aided with model use and policy testing for answering sub-question 3. Future scenarios for trade volumes in the hinterland truck transport system can be implemented, based on literature research. Furthermore, the insights about the intrinsic working of interventions that implement the selected technologies can be translated to implementable interventions in the system dynamics model. The new technology measures that lie within the mandate of the Port of Rotterdam Authority can be tested as interventions in the system. Its effectiveness in the year of 2050 can be measured based on KPIs defined for sub-question 2.

3.3. Answering the main research question

The modeling results from sub-question 3, that score the technological measures on the list of identified KPIs, are used to answer the main research question. The combination of scores on these KPIs are

assessed jointly based on the preferences of the Port of Rotterdam Authority, resulting in a ‘most viable technology’. Recommendations are defined that focus on the requirements for implementation and timing of these technologies. Sub-question 2 is at the base of this answer, since it showcases the underlying dynamics at play in the system, that greatly influence technology adoption. It does so by demarcating a scientifically novel system, by combining interdependent sub-systems in one aggregated model for the specific case of the Port of Rotterdam, which was found to be a knowledge gap. Sub-question 1 delivers the most relevant carbon intensity of truck energy reducing technologies and a framework to assess these technologies, as well as providing the knowledge for correct implementation in the SD-model.

4

Technologies for reduction of carbon intensity of energy

Various technological options exist for the reduction of carbon intensity of trucks by their fuel use. In this chapter, the three most promising technological alternatives for reducing carbon intensity of energy specifically for the Port of Rotterdam are discussed: Battery Electric Trucks, Fuel-Cell Electric Trucks and e-diesel technology (Lechtenböhmer et al., 2018). The research focuses on well-established, easily deployable solutions to lower the carbon intensity of energy in hinterland truck transportation at the Port of Rotterdam. The research favors technologies that are already well-documented in the literature, allowing for more accurate modeling and aiding medium-term decarbonization as expected by the adopted climate goals. For example, hydrogen dual-fuel trucks offer possibilities through minimum diesel truck adaptations and less reliance on hydrogen stations, but are less mature and therefore excluded from the technology selection. Also, within the category of BETs only static charging has been included in the scope of this research. Dynamic charging with overhead lines, conductive road charging or inductive road charging deliver the same energy efficiency as BETs driving on own batteries. Dynamic charging would require larger investments for the dynamic charging infrastructure and deviates more from the current charging practice. Therefore, static charging is chosen as the representative subclass of truck electrification options that aligns best with the Port of Rotterdam hinterland transport. Lastly, biofuels are not included as a technology due to their high land use requirements and methane releases from biomass gasification processes and CO₂-releases from agricultural soils and from forestry (Erb et al., 2018).

The technologies are discussed based on factors that are essential for these technologies in becoming viable alternatives for reducing carbon intensity of energy of trucks in the Port of Rotterdam hinterland transport. Sections were derived from interviews and are devoted to the crucial factors of charging infrastructure that allows for fast and flexible truck transport, maturity and adoption rate of the technology, lifecycle costs and energy efficiency, and availability of the required energy source. This chapter is guided by the following subquestion:

Which technologies for reduction of carbon intensity of energy for trucks align with the position of the port of Rotterdam as energy hub?

4.1. Charging infrastructure

A deficit of charging infrastructure is a serious challenge to the adoption of new truck types, as highlighted by both industry and research (ACEA, 2021; Al-Hanahi et al., 2021). Without a sufficiently dense network of charging stations, the new technologies do not align with the current practices of trucking companies (Raoufi et al., 2025). Destinations in the hinterland with a high distance to the nearest charging station will be harder or impossible to reach. Also, waiting times at charging stations - especially those at crucial links in the charging infrastructure network - will increase, thereby increasing operational cost of the trucking companies and reducing attractiveness of the new technology. Therefore, per technology it is researched what a charging infrastructure network would entail that could accommodate the adoption of this technology in Port of Rotterdam truck hinterland transport.

4.1.1. Required charging infrastructure Battery Electric Truck

Although an elaborate network of charging stations for electric passenger cars has been constructed in The Netherlands over the last decade, creating sufficient charging infrastructure for BETs is more challenging due to their higher charging power demands, which requires larger infrastructural investments (ACEA, 2021; Al-Hanahi et al., 2021). However, these high investment costs for BET charging infrastructure are mitigated because charging infrastructure can be gradually scaled from short-haul to long-haul applications as battery technology improves. Given that 90% of truck hinterland transport drives to or from the Port of Rotterdam stays within Dutch borders and is therefore a maximum of about 280 kilometres, the share of short-haul in truck hinterland transport is very large (Port of Rotterdam, n.d.-b). In addition, the range of BETs is about 483 kilometres (Burke & Sinha, 2020), so a return trip is feasible for almost all hinterland locations in The Netherlands, especially given the lower electricity use of BETs on an empty return trip. This is important for the operational and financial feasibility of truck hinterland transport (Kin et al., 2021).

Depot charging stations

This large percentage of short-haul trips in truck hinterland transport for the Port of Rotterdam allows for the introduction of depot charging as a viable alternative for charging infrastructure of BETs. Truck hinterland transport with depot charging at the central transport node of the Port of Rotterdam presents multiple factors that make the adoption of depot charging attractive.

First of all, depot charging can make use of cheaper electricity than en-route charging, because it can time its charging around off-peak timeslots and the price of electricity drops if it is used in larger quantities like at one specific depot (Kin et al., 2021). Also, depot charging can make use of the alternating current charging method, with a power up to a maximum of 44 kilo-Watt (kW) (Speth & Plötz, 2024). This low power requires also less infrastructural investments for delivering high power such as thicker cables, larger transformers and more robust grid components (Al-Hanahi et al., 2021). This limited infrastructural investment lowers the price charged to consumers, as well as shortening construction time of the charging infrastructure to not hamper the adoption of BETs.

Depot charging does take more time due to its low power charging system. However, the depot is a node with high connectivity to other nodes in the hinterland truck transport because it is always serves as destination or origin. This means that it is passed through by hinterland trucks often, allowing for strategic alignment of breaks with depot charging. With the low power of maximally 44 kW charging takes about 7 hours for a 300 kilo-Watt-hour (kWh) battery size, with charging time being reduced when charging occurs from 20% to 80% of battery capacity. This charging time can take place at moments when one truck driver ends their shift, a primary stop event (Dimatulac et al., 2023). These primary stop events occur often, since in the EU shift changes mandatorily have to occur after 9 hours of driving (European Parliament and Council of the European Union, 2006). By planning charging in between driver shifts, no dwelling cost is incurred for continued payment of the driver. Alternatively, secondary stops that are actually dedicated to refuelling, prove to accommodate the longer refuelling time (Dimatulac et al., 2023). Because secondary steps are also used for resting, Figure 4.1 shows that 18.21% of secondary stops takes more than 8 hours for trucks operating in Canada (Dimatulac et al., 2023).

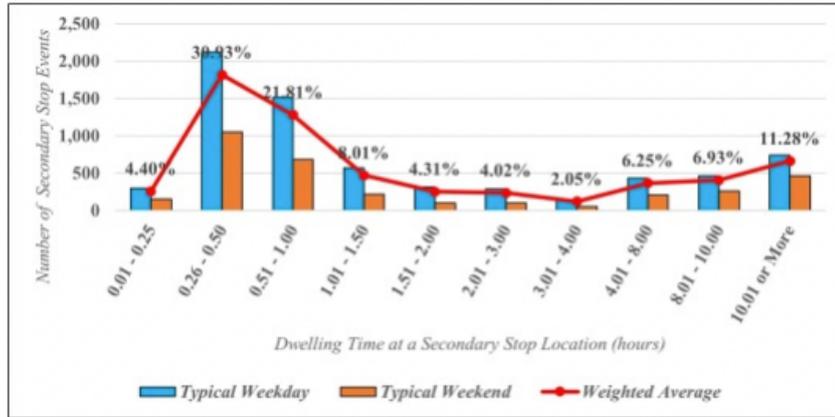


Figure 4.1: Dwelling time for secondary stops (Dimatulac et al., 2023)

Fast-charging stations

Fast-charging with high charging power - often of 350 kW - is especially relevant for long-haul trucks (Speth & Plötz, 2024). These long-haul distances fall outside of the range of BETs and therefore en-route fast charging is essential to avoid dwelling time. Dwelling time with a driver present leads to increased costs that make the use of BETs for long-haul freight financially not viable. For that reason, high power is used with fast-charging, allowing for low dwelling times as shown in Table 4.1 for different well-known BET brands and types.

Brand	Charging time
Tesla	0.5 hour (Qayyah, 2019)
MAN	1 hour (MAN Germany, 2021)
Freightliner eCascadia	1.5 hour (Freightliner Trucks, 2021a)
Freightliner eM2	1 hour (Freightliner Trucks, 2021b)

Table 4.1: Fast charging time for common BETs

These fast charging times align well with mandatory breaks for truck drivers in the EU, that have to occur after every 4.5 hours of driving (European Parliament and Council of the European Union, 2006). The driver can rest up while the truck is parked at a fast-charging station. Not for all types of trucks in Table 4.1 the charging time is completely covered by the mandatory break time, but a large part of the charging time does not cause extra dwelling cost that the trucking company would not have incurred anyways due to mandatory break regulation of the EU.

Choice for depot charging

Although fast-charging stations are more easily implemented in the current operational strategy of trucking companies, as they offer more flexibility and lower charging times that can largely overlap with mandatory driver breaks, in this study this type of charging infrastructure for BETs is not included. That is because no suitable data has been found for the routing of trucks that drive for the Port of Rotterdam, also for drives performed for other clients than the Port of Rotterdam, which makes it difficult to assign optimal locations for fast-charging stations. Furthermore, the Port of Rotterdam Authority has little say in the distribution of fast-charging stations along busy truck hinterland routes, and has to rely on the supply side of the fast-charging infrastructure market to initiate these fast-charging stations and other government bodies such as municipalities and Ministries to approve these fast-charging station plans.

Depot charging shows advantages as the preferred charging option for energy hubs that act as transport nodes with a high connectivity, such as the Port of Rotterdam. The long charging time associated with the alternating current charging method, can be (partly) compensated for by a lower electricity cost. Changing to this new model of depot charging would require a vast change to the operational strategy

of these trucking companies, which is possible in the middle-term of several decades that this study uses (Tavasszy et al., 2023).

4.1.2. Required charging infrastructure Fuel-Cell Electric Truck

The adoption of FCETs is dependent on the deployment of specialized hydrogen refuelling stations. Since most FCETs drive on compressed gaseous hydrogen instead of liquid hydrogen, the refuelling operation has to be tailored to delivering the hydrogen in gaseous form to FCETs (Lee et al., 2018). Due to the many components required for a hydrogen refuelling station, capital costs are estimated at €2.21 million (Wulf & Zapp, 2021). However, these costs are spread out over the long technical lifetime of 10 years (Wulf & Kaltschmitt, 2012). For the gaseous refueling process a generic hydrogen refueling station requires the following components:

- Storage tanks
- Hydrogen compressors
- Dispensers for refueling
- a cooling unit that can lower the temperature of gaseous hydrogen to -40°C (Cebolla et al., 2015; Xiao et al., 2016)
- Safety equipment to prevent and mitigate leaks and explosions, such as sensors, safety valves and dry fire extinguishing systems (Liang et al., 2019; Qian et al., 2020)

An important advantage of FCETs is that refuelling requires less than 5 minutes (Mancino et al., 2023). This is a small fraction of the refuelling time for BETs, and is even slightly faster than the refuelling time for diesel trucks of 15 minutes (Giuliano et al., 2021). However, the distance to a nearest hydrogen refuelling station should not be too long, in order to accommodate all transport routes.

Because of the novelty of hydrogen-driven vehicles, the infrastructure for hydrogen refuelling stations is still in its infancy (Genovese & Fragiaco, 2023). In 2019 there were only about 185 hydrogen refuelling stations in entire Europe (Genovese & Fragiaco, 2023). 23 of those are located in The Netherlands (H2Benelux, 2024). At present, the average hydrogen refuelling station can store between 100 and 500 kg of gaseous H₂ per day (Genovese & Fragiaco, 2023). Due to this low number of current hydrogen refuelling stations, a common strategy is the cluster technique, which entails clustering hydrogen refuelling stations in areas identified as early FCET markets by public-private partnerships (Genovese & Fragiaco, 2023). In order to set up an efficient cluster network, these public-private partnerships must address all relevant building blocks for adoption by including truck producers, trucking companies, refuelling station operators and government bodies. Compared to previous strategies, this cluster technique enables more efficient refueling networks, reduces costs, and facilitates cost-effective hydrogen distribution (Hydrogen Europe, 2020). In Germany alone, there are about 81 stations, which means it could be a promising partner to apply the "cluster technique" to (Genovese & Fragiaco, 2023). This strategy is already being applied to a transport cluster that the Port of Rotterdam belongs to; in 2022 a project was announced to have 1000 FCETs driving on green hydrogen in the next few years between the Port of Rotterdam, the Port of Antwerp and Duisburg (Rotterdam Maritime Capital, 2022). Thereby it connects two large port clusters in Northwestern Europe with the Ruhr area, underlining the role that energy hubs can play in the adoption of FCETs.

4.1.3. Required charging infrastructure e-diesel

When e-diesel produced by the Power to Liquid process complies with EN 15940, its properties show great similarities with diesel (Royal Netherlands Standardization Institute, 2023). That means that it can be used as a fuel for internal combustion engines of modern trucks without engine modifications. Given that trucks in The Netherlands are exported on average at an age of 8 years (Bhoraskar & Mulder, 2023), the truck fleet under consideration for the Port of Rotterdam falls under this category of modern trucks that require no engine modifications for the use of e-diesel. Therefore, trucks can use diesel and e-diesel interchangeably and e-diesel can be offered at the same refuelling stations as where diesel is offered. This can be done simply by adding more pumps at existing refuelling stations, either with a blend of e-diesel and diesel or with pure e-diesel.

4.2. Maturity and adoption rate of carbon reduction of energy technologies

Adoption rate in this research is defined per technology as the number of trucks in the Port of Rotterdam truck fleet driven by this technology divided by the total number of trucks in the Port of Rotterdam truck fleet (Raofi et al., 2025). Thereby, definitions of the broader term awareness that take into account the underlying processes of awareness such as feedback from consumers' experience, word of mouth and marketing are not considered (Struben & Sterman, 2008). Instead, a more direct approach with adoption rate is taken that measures the effects that these underlying processes have had by increasing sales of that technology.

Closely linked to adoption rate is the maturity of a technology. The maturity of a technology measures both the reliability of a technology and its performance (Nieuwenhuijsen et al., 2018). Reliability and performance of a technology can increase with technological or operational advancements, such as automation in the production process or increased safety measures to the technology. These advancements are funded by R&D expenses (Nieuwenhuijsen et al., 2018). Adoption rate and maturity in this study only matter for competing technologies, namely the different truck types, so they are not discussed for e-diesel as an alternative for diesel in existing internal combustion engines.

4.2.1. Maturity and adoption rate Battery Electric Truck

The adoption rate level of BETs for the Port of Rotterdam truck fleet is based on data for all trucks in The Netherlands. In 2023, only 0.9% of trucks in The Netherlands was a BET (European Automobile Manufacturers' Association (ACEA), 2025). Given that the total number of trucks on the roads in The Netherlands is 165522, this means that there are about 1500 BETs driving in The Netherlands (European Automobile Manufacturers' Association (ACEA), 2025). Literature research has not delivered more recent data, although it would have been useful to accurately measure up-to-date adoption rate of a technology for which yearly numbers can differ greatly because of its recent emergence.

Since diesel is a fuel with a high energy-density, BETs have difficulty competing by achieving the same driving range, especially for long distance transport (Nykvist & Olsson, 2021). Diesel trucks across different types have a driving range of about 1207-3540 km, allowing them to do multiple cargo transports without refuelling (Burke & Sinha, 2020). For BETs this range is only about 480 km (Burke & Sinha, 2020). One vital direction for increasing BET maturity is to appoint R&D-budgets to upscaling of the battery capacity of BETs in order to increase their driving range (Çabukoglu et al., 2018; Earl et al., 2018).

4.2.2. Maturity and adoption rate Fuel-Cell Electric Truck

In part due to the infancy of charging infrastructure, adoption rate of FCETs is very low in The Netherlands. Estimations about the precise number of FCETs are scarce, but one estimation shows that about 100 FCETs have been sold since 2021 (International Council on Clean Transportation (ICCT), 2023). The early adoption of FCETs is largely led by subsidized pilot initiatives. The Port of Rotterdam Authority is collaborating in the Clean Hydrogen and Road Transport Project (CH2aRT) with hydrogen refuelling station operator Air Products, trucking company Schenk and research institution TNO (Port of Rotterdam, 2022). This project aims to create the largest hydrogen refuelling station in The Netherlands as of yet close to the Port of Rotterdam to accommodate three FCETs owned by Schenk. The subsidized aspect of this project shows that the technology is not able to sustain itself as of yet and will need to obtain a higher level of maturity before it can be considered a competitor for diesel trucks.

For the most promising subtype of fuel-cells, the proton exchange membrane fuel cell, R&D-backed improvements seek to enhance technology maturity by looking at the dynamics and performance of the fuel-cell stack. The central problems in these stacks are control of power, temperature and water (Aminudin et al., 2023). Research is still ongoing to improve conditions for lower membrane dehydration, water flooding and reactant deficits (Aminudin et al., 2023).

4.3. Energy source availability for carbon intensity of energy reducing technologies

The transition to lower carbon intensity of energy technologies requires the use of new energy sources that are not yet abundantly present in the energy mix. Specifically for the energy hub of the Port of Rotterdam it is discussed in the following sections which energy sources are required and whether it is able to supply these energy sources in the right quantities.

4.3.1. Availability of energy source Battery Electric Truck

Among other EU member states, The Netherlands is in a relatively good position to transition from diesel trucks to BETs, due to the affordable electricity price in comparison to the price of diesel (Noll et al., 2022). Especially in an energy cluster such as the Port of Rotterdam there are additional options to increase affordability due to the proximity to electricity production sites. When the charging infrastructure of depot charging for BETs is adopted, it is also possible in the Port of Rotterdam to plan charging breaks ahead up to 48 hours (Distro Energy, 2025). That way, the most affordable electricity price can be obtained, making the depot charging option more attractive for trucking companies.

Wind at sea forms an important source of green electricity. In 2023 there was 330 Mega-Watt (MW) of installed wind capacity, with plans to further increase this to 7.4 Giga-Watt (GW) by 2030 (Port of Rotterdam Authority, n.d.d). For 2050 the plan is to further develop capacity to 60-70 GW (Port of Rotterdam Authority, 2023b). The Port of Rotterdam also takes an active role in upscaling the availability of wind electricity in the port. For example, it has taken a 50% share in Rotterdam Shore Power, a joint venture together with energy company Eneco (Port of Rotterdam Authority, 2023c). To a lesser extent there is also electricity generated by solar power available in the Port of Rotterdam. There is 90 MWp of installed capacity (Port of Rotterdam Authority, n.d.d). Extra solar parks can be placed between wind parks, almost doubling the capacity of a wind farm, at the condition that a larger battery size is made possible that can store the electricity before it is transported to shore (TU Delft, n.d.).

4.3.2. Availability of energy source Fuel-Cell Electric Truck

In 2022, less than 2% of Europe's energy consumption came from hydrogen, which was mostly utilized to make chemical products like fertilizers and plastics (European Commission, 2024). Almost all of this hydrogen was grey because natural gas was used to manufacture 96% of this hydrogen, which resulted in large CO₂ emissions (European Commission, 2024). Therefore, the European Commission (EC) has included in its hydrogen policy framework in 2023 as part of the 'Fit for 55 package' binding targets for the use of green hydrogen in transport (European Commission, 2024). Although the Port of Rotterdam is working on blue hydrogen projects, it is not included in this hydrogen policy framework. That is because the technology is seen as transitional due to its methane leakage, residual CO₂ emissions, greater prices than grey hydrogen, and the North Sea's low CCS capability. In order to concentrate on long-term sustainable solutions, blue hydrogen is not included in this analysis because it aims to have truck hinterland transport that is carbon-neutral by 2050. However, recent investigations by renowned public research institutions in The Netherlands have predicted that for the next 15 years production cost of green hydrogen will be 5 to 6 times as high as production cost from grey hydrogen, (European Commission, 2024; PBL Netherlands Environmental Assessment Agency, 2024). This cost of green hydrogen is so high due to the capital and operational cost of the electrolyzer. It is expected that capital cost will lower due to increased maturity by 2030, instigated by the revenue generated by mandatory use of green hydrogen due to the hydrogen policy framework from the EC (European Commission, 2024). Still, operational cost are projected to remain high due to electricity and net connection prices (PBL Netherlands Environmental Assessment Agency, 2024). TNO estimates the cost price of green hydrogen for 2030 at 10 euros per kilogram, with no indication for this study that the price of green hydrogen will lower beyond this moment (TNO, 2024).

In the Port of Rotterdam, green hydrogen capacity is being created to align with the EU hydrogen policy framework and to position itself as Europe's green hydrogen hub. In 2022 there were plans from multiple energy companies - BP, Shell, NESTE and Nourion - to construct electrolyzers on the Port of Rotterdam Maasvlakte, although it is unsure whether these projects will take place. When realized,

green hydrogen production in the Port of Rotterdam is estimated at 2 GW for 2030, which under current production processes is capable of producing 0.32 Mt of green hydrogen (Rotterdam Maritime Capital, 2022). Due to the projected steep increase in demand, the Port of Rotterdam aims to have capacity for the production of 2 Mt of green hydrogen in its cluster by 2050 (Port of Rotterdam Authority, 2022).

Given that demand for hydrogen exceeds local production with a projected demand of 20 Mt for 2050, import will form an important part of the green hydrogen supply (Port of Rotterdam Authority, 2022). In its capacity as a matchmaker, the Port of Rotterdam Authority has signed contracts with nations and ports across the globe that will soon be able to export significant amounts of green or low-carbon hydrogen. (Port of Rotterdam Authority, n.d.e). For example, the Port of Rotterdam has a memorandum of understanding with the Port of Pecém in Brazil to strengthen its transport infrastructure to accommodate more green hydrogen trade in the future (Port of Rotterdam Authority, n.d.f). Hydrogen import is expected to encompass 0.2 Mt of green hydrogen by 2030 (Rotterdam Maritime Capital, 2022). By 2050, green hydrogen import is expected to consist of 18 Mt, also serving a broader area in Northwestern Europe (Port of Rotterdam Authority, 2022).

4.3.3. Required energy source e-diesel

Multiple production routes for the production of e-diesel have been discussed in literature (Saric et al., 2021). From these routes, the MeOH route is the most cost-effective and efficient way to generate e-diesel. Due to the high power consumption for the MeOH route of 0.37 MWh/t and a high Levelized Cost Of Electricity (LCOE) in The Netherlands, the e-diesel from this process is cheaper to import. A country with a low LCOE that was used for the analysis was Canada (Saric et al., 2021). While the increased costs are very minimal, the production step from the intermediate of this route to diesel produces a better value product. Although it would be financially attractive to perform this step in The Netherlands, it makes sense that the intermediate's conversion into the finished diesel product is done by the exporting country. Costs for the Fischer-Tropsch manufacturing route are comparable to those of the MeOH process (Saric et al., 2021). However, given that MeOH is a platform molecule for the chemical industry and that there is currently a global market for MeOH, it makes more sense to import green MeOH to make diesel (Saric et al., 2021).

4.4. Comparison of lifecycle costs and energy efficiency of technologies

Lifecycle costs (LCO) specific to the different carbon intensity of energy reducing technologies are essential for the adoption decisions made by trucking companies. Therefore, LCO is also important for obtaining the goals of the Port of Rotterdam that wishes to steer adoption towards lower-emission technologies. LCO also includes cost per kilometer driven by a truck, which is why energy efficiency is also included in this section. Carbon intensity is based on Well-to-Wheel emissions, taking into account the whole production process of the energy source. Additional LCO costs that apply to all of the different carbon intensity of energy reducing technologies, such as tolls and tyres, are not included in this section but are addressed in this study. From various sources the search results have been gathered and presented in Table 4.2. To improve confidence in the values, parameter ranges are constructed based on multiple sources, whenever these were retrieved.

Variable	ICE diesel	BET	FCET	ICE with e-diesel
Energy Component Cost	118 \$/kW	101–175 \$/kW	120–750 \$/kW (Burke & Sinha, 2020)	118 \$/kW
Energy Efficiency	35%	62%	29%	43.4% (Leonzio et al., 2024)
Price of Fuel Used	1.71 €/L	0.069 €/kWh (Schmitt et al., 2024)	Grey: 3.5 €/kg, Green: 12–14 €/kg (Autoriteit Consument & Markt (ACM), 2023)	4.5 €/L [Interview 3]
Fuel per km	0.30–0.35 L/km	1.7–2.2 kWh/km (Volvo FH Electric, eActros)	2.1–2.9 kWh/km (Hyundai XCIENT, Nikola Tre FCET)	0.30–0.35 L/km
Carbon Intensity	100.45 gCO ₂ e/MJ (Giuliano et al., 2021)	93.75 gCO ₂ e/MJ (Giuliano et al., 2021)	100 gCO ₂ e/MJ (International Energy Agency (IEA), 2023)	64.07 gCO ₂ e/MJ (Giuliano et al., 2021)
CO ₂ -emissions per km	1618 gCO ₂ e/km (Giuliano et al., 2021)	574–743 gCO ₂ e/km	756–1044 gCO ₂ e/km	688–918 gCO ₂ e/km
Truck Price	123,000–140,000 \$ (Burke & Sinha, 2020; Giuliano et al., 2021)	340985 \$ + variable battery cost (Burke & Sinha, 2020)	232500 \$ + variable battery cost (Burke & Sinha, 2020)	123,000–140,000 \$ (Burke & Sinha, 2020; Giuliano et al., 2021)
5-year TCO	0.78–0.97 \$/mile (Burke & Sinha, 2020)	0.58–1.42 \$/mile (Burke & Sinha, 2020)	0.77–1.32 \$/mile (Burke & Sinha, 2020)	0.78–0.97 \$/mile (Burke & Sinha, 2020)
Lifetime	12 years (Raooifi et al., 2025)	12 years, 6 for battery (Noll et al., 2022)	12 years, 6 for battery (Noll et al., 2022)	-

Table 4.2: Comparison of lifecycle costs and energy efficiencies

From the results in Table 4.2 it is derived that the initial investment in both lower-emission trucks requires a larger investment upfront, due to its higher truck price. This investment is further enlarged during the lifetime of a BET or FCET, with a costly battery replacement halfway its lifetime (Noll et al., 2022). Therefore, it is important for these lower-emission trucks to operate with lower Operational Expenditures (OPEX) throughout its lifetime. In Table 4.2 relevant numbers are collected that are used later in this research to calculate yearly Total Cost Of Operation (TCO) as a base of comparison for the different carbon intensity of energy reducing technologies. Future developments influencing TCO, such as increased CO₂-emissions tax under the EU Emissions Trading System (ETS) 2 scheme, play a role in the development of yearly TCO for the different carbon intensity of energy reducing technologies. Therefore, no independent TCO-calculation nor statements about the coherence of variables are made as of yet. However, in this section indications of a 5-year TCO from literature have been given. Comparison shows similar averages for the different carbon intensity of energy reducing technologies, except FCET that has a higher average 5-year TCO. However, the size of the parameter ranges differ, with those of the developing technologies of BETs and FCETs being characterized by larger uncertainty and thus larger parameter ranges.

4.5. Advantages and downsides of carbon intensity of energy reducing technologies

In Table 4.3 the advantages and downsides of the selected carbon intensity of energy reducing technologies discussed in this chapter are highlighted.

Technology	Advantage	Downside
BET	<ul style="list-style-type: none"> + Most mature alternative to diesel trucks + Green electricity can be produced locally 	<ul style="list-style-type: none"> - Battery replacement every 4–6 years, leading to environmental pollution - Shortest driving range
FCET	<ul style="list-style-type: none"> + Long driving range 	<ul style="list-style-type: none"> - Battery replacement every 4–6 years, leading to environmental pollution - Highest truck price - Fluctuating H₂ price
E-diesel	<ul style="list-style-type: none"> + Charging infrastructure easy to implement + Does not require new truck adoption 	<ul style="list-style-type: none"> - Pricewise not competitive with diesel

Table 4.3: Advantages and downsides of carbon intensity of energy reducing technologies

The methodology used in this chapter has not yet uncovered how these different advantages and downsides contribute to the relative attractiveness of adopting this technology. Therefore, it is not sure to what extent these technologies will be adopted by trucking companies and how this level of adoption contributes to obtaining the goals of the Port of Rotterdam. The chapter has delivered relevant insights into the relevant factors underlying these technologies, but quantified research into their coherence and development over time are required to steer informed discussions about policy recommendations.

5

Relevant Systemic Dynamics

It is unsure how these technologies for reduction of carbon intensity of energy score on the various KPIs in the medium-term. System dynamics is able to capture these different KPIs and calculate these for the medium-term, by taking into account relevant hinterland transport feedback loops and delays that cause enlarged effects in the medium-term. The hinterland transport system is split up into relevant sub-systems in the step of conceptualisation. Furthermore, KPIs are appointed across these sub-systems that capture the value of new truck adoption for the Port of Rotterdam Authority. In order to discover sensitivities in the model to base policies on, the conceptual model has to be realized in an SD-environment, which happens in the modelling step of formulation per sub-model. Afterwards, the model has to be evaluated for correctness and validity. Lastly, the systemic impact of container volume throughput is assessed through the use of different scenarios.

In this chapter, the following subquestion can be answered:

2. How can the relevant dynamic factors for transition to lower carbon intensive energy for truck hinterland transport of the port of Rotterdam be formalized in a System Dynamics model?

5.1. Problem articulation

Given that 13.7 of the 16.8 Gt_{km} of truck hinterland transport involves the transportation of containers of general cargo in containers, the type of truck under consideration is limited to tractor-trailer trucks that can transport containers (Lechtenböhmer et al., 2018). The tractor-trailer truck falls under the category of heavy goods vehicles in the EU, a category that encompasses all lorries with a gross combination mass of over 3.5 tonnes, covering both subcategories N2 and N3 (European Commission, 2001). Because almost all heavy tractor semi-trailers are E6-type, which is the most clean and up-to-date standard for trucks in the EU, no distinction needs to be made in the system dynamics model between class E4-E5-E6 (Bhoraskar & Mulder, 2023).

Tractor-trailer trucks are mostly used for the container transport to/from specific locations in the hinterland, that can not be reached by inland vessel or train. Either by performing the whole trip to/from the port, or through a multimodal transport in which the tractor-trailer truck does the first/last leg that requires the most routing flexibility. A percentage of the total number of Dutch tractor-trailer trucks that corresponds with the trade volumes of the Port of Rotterdam hinterland transport is considered as the fleet of hinterland trucks, aggregating fleets of individual transport companies. These trucks perform container transports for the Port of Rotterdam, but not exclusively. That means that they also perform container transports to/from other locations, in order to include more transports in its routing and optimize the cost-efficiency of its operation. However, these other drives fall outside of the scope of truck hinterland transport for the Port of Rotterdam.

The analysis uses a 25-year timeframe, from 2025 to 2050. This timeline supports both short-term deployment and medium-term system change, and is in line with the port authority's strategic planning goals of becoming climate neutral by 2050 in alignment with the European Green Deal and the Paris Agreement. To make sure the model represents current reality right away, initial circumstances are taken from the most recent and pertinent government and industry sources. This study intends to offer useful insights for the Port of Rotterdam Authority by focusing on a particular high-impact transportation

mode and using a precisely specified time horizon. Supporting evidence-based choices that complement the Port of Rotterdam's and its stakeholders' larger decarbonization objectives is the aim.

5.2. Conceptualisation

Conceptualisation consists of multiple processes that aid in the determination of system boundaries, discovery of the major systemic mechanisms and to describe the expected system behaviour. These processes are discussed in the following sub-sections: System demarcation, choice of KPIs, diagramming system causality, identification of feedback loops, identification of delays and the formulation of dynamic hypotheses.

5.2.1. System demarcation

To deliver a valuable contribution to the evidence-based decisions for the future of hinterland truck transport of the Port of Rotterdam, multiple facets for a successful transition have to be included in this fleet-centred model. These aspects stem from the sections of Chapter 4, while transport volume is also included due to its interaction with adoption and the expected growth of this variable in the future for the Port of Rotterdam. These aspects are included as sub-models in the system dynamics model, with their dynamic interactions forming the core of this research. These sub-models, further elaborated on in the formulation step, are:

- Truck hinterland transport
- Adoption of lower-emission trucks
- CO₂-emission from truck hinterland transport
- Charging infrastructure
- Energy source availability

5.2.2. Choice of Key Performance Indicators

Since the success of the transition towards a decarbonized truck hinterland transport depends on the performance of all these sub-models, KPIs have been appointed in all sub-models to measure its state. The KPIs are interpreted from the perspective of the Port of Rotterdam Authority, because this actor presents the broadest set of interests of all port actors and is the actor that has committed itself to becoming a carbon-neutral port by 2050. This balanced set of interests from the Port of Rotterdam Authority is represented by the following set of KPIs, present in the system dynamics model:

- CO₂-emission from Hinterland truck transport
- Transport price per Mtkm for Hinterland truck transport
- Adoption of truck with lower carbon capacity of energy
- Charging infrastructure built
- Energy source availability

First of all, the Port of Rotterdam has set itself the goal to align with the European Green Deal by becoming a climate-neutral port by 2050, as well as reducing 90% of the CO₂-emissions by 2030 in comparison to 2019 (Port of Rotterdam Authority, 2023a). To measure the success in achieving this short-term and medium-term goal, the KPI of *CO₂-emission from Hinterland truck transport* is measured as grammes of CO₂-emission from hinterland truck transport. If carbon neutrality of truck hinterland transport is to be obtained, this curve should flatten out over the runtime of the model.

Secondly, *Transport price per Mtkm for Hinterland truck transport* is important for trade demand in the Port of Rotterdam. This KPI is measured as the amount of euros it costs to transport a megatonne of container freight for a kilometer. If this price is low, this is calculated into the eventual price of the product that is shipped through the Port of Rotterdam, making the Port of Rotterdam a more competitive choice for cargo throughput in comparison to other transport hubs.

Thirdly, *Adoption of truck with lower carbon capacity of energy* provides a measure of how far the Port of Rotterdam is on its path towards lower CO₂-emission Hinterland truck transport. Although this is also measured more directly with *CO₂-emission from Hinterland truck transport*, the KPI does provide a measure of where in the process the Port of Rotterdam is, which provides insights for the future past

the horizon of 2050. The *Adoption of truck with lower carbon capacity of energy* is measured separately for adoption of BETs and of FCETs, as the percentages of these types of the total truck fleet.

Whether this *Adoption of truck with lower carbon capacity of energy* is possible, depends partly on the *Charging infrastructure built*. The availability of sufficient charging infrastructure is an important factor underlying the investment decision of a trucking company into a truck with a lower carbon capacity of energy. Given the different charging infrastructure needs for BETs and FCETs, the *Charging infrastructure built* is calculated separately for these two lower-emission truck types. Both in an absolute form that displays the total number of charging stations, as well as in relative form where the charging capacity of these existing charging stations is compared with the demand for these from the Port of Rotterdam hinterland truck fleet.

Lastly, the *Adoption of truck with lower carbon capacity of energy* requires the availability of energy sources for which the Port of Rotterdam is currently still building up the capacity. Therefore, *Energy source availability* in the Port of Rotterdam is calculated for both hydrogen and electricity, in order to assess whether the transition is not hampered by a shortage of the required energy sources. Availability is measured as a fraction of total supply of an energy source in the Port of Rotterdam, after which an assessment is made whether this fraction is reasonable for truck hinterland transport.

5.2.3. Causality in the system

A high-level method of showing the interaction between the submodels from the system demarcation is with the construction of a causal loop diagram. The causal relations between the submodels are non-quantified positive or negative relations, that decide the outcomes of the KPIs defined for this model. The causal loop diagram is displayed in Figure 5.1.

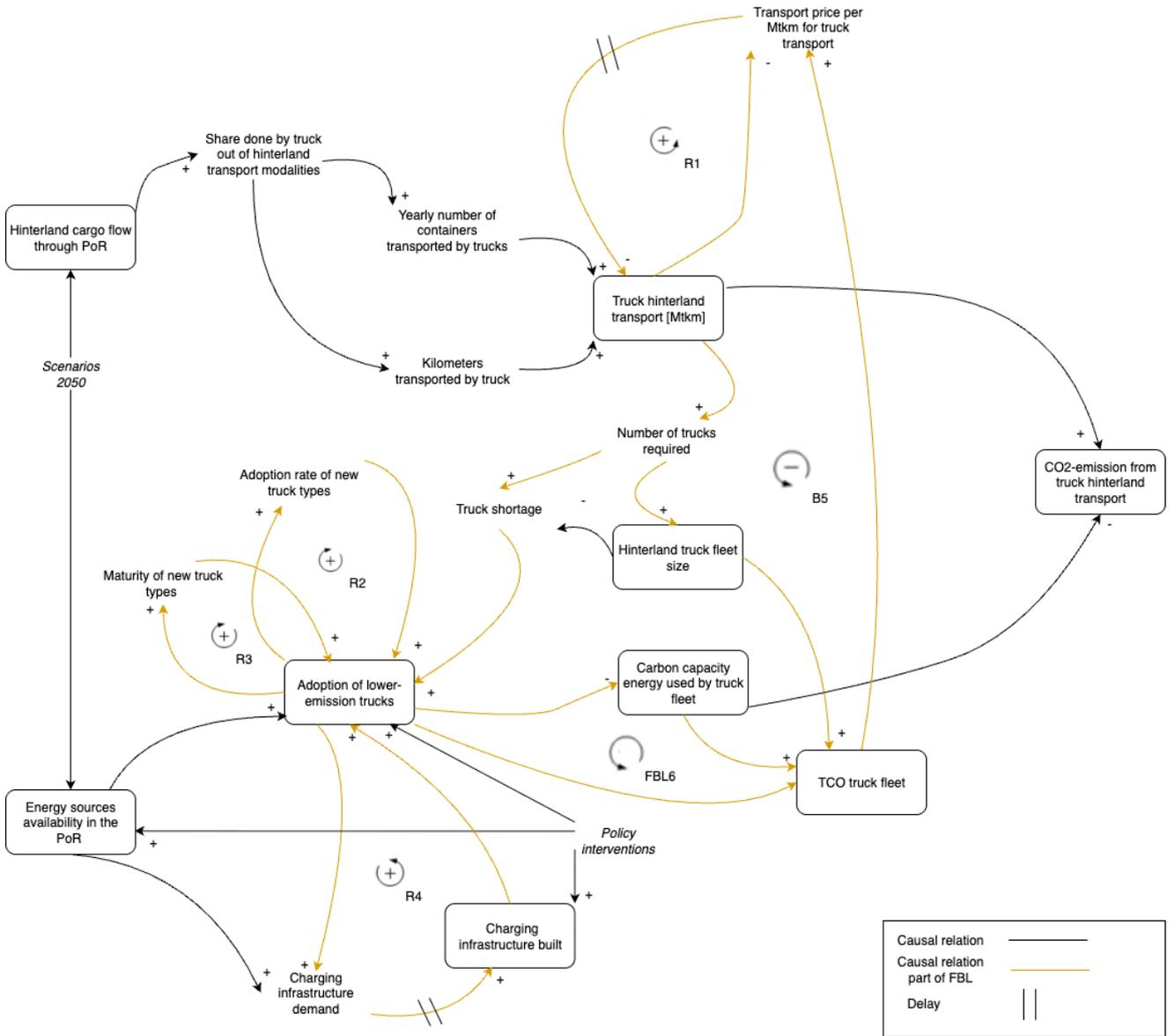


Figure 5.1: Causal loop diagram

5.2.4. Feedback loops in the system

Not only do the sub-systems have an effect on one another, the effects also in occasions form the basis of feedback loops. Two or more connections between variables that are related so that, if one starts at any variable in the loop and follows the arrows, one eventually returns to the first variable make up a feedback loop (Auping et al., 2024). Feedback loops are said to be reinforcing if an initial increase in variable A results in a subsequent increase in A, and if an initial decrease in A results in a drop in A through the relation with variable B in the feedback loop (Auping et al., 2024). On the contrary, feedback loops are said to be balancing if an initial increase in variable A results in a subsequent drop in A, and if an initial decrease in A results in an increase in A through the relation with variable B in the feedback loop (Auping et al., 2024). Six involved feedback loops have been retrieved from literature and have been displayed in the Causal-Loop Diagram in Figure 5.1:

- **Transport price attractiveness (R1):** The basis for this feedback loop is the price elasticity of *Hinterland truck transport [Mtkm]* to *Transport price per Mtkm for truck transport* (De Jong et al., 2010). When *Transport price per Mtkm for truck transport* increases, it negatively influences the demand for truck transport in the Port of Rotterdam because suppliers can divert to markets

with cheaper transportation costs. When *Mtkm for truck transport* decreases, the TCO for the truck fleet is divided over a lower number of trips, meaning the *Transport price per Mtkm for truck transport* increases more than the original rise that instigated the feedback loop.

- **Word-of-mouth (R2):** The interplay between adoption of a new technology and its adoption rate has been a driving factor for the volatile market uptake of new technologies. The likelihood of people finding out about lower-emission truck options through media attention or from competitors will rise as its fleet size increases. People will become more confident in the technology's dependability and functionality as they observe more examples in their surroundings. The appeal of this new technology is enhanced by this confidence (Nieuwenhuijsen et al., 2018).
- **R&D cycle (R3):** Technology maturity has a similar reinforcing effect on the adoption of a new technology as adoption rate. Adoption of a new technology generates sales revenue that can be devoted to the further development of the technology. This research and development increases the performance and reliability of the new truck types, for which promising research fields have been identified in Section 4.2.1 and Section 4.2.2. The appeal of the new technologies is enhanced by these technological improvements (Nieuwenhuijsen et al., 2018).
- **Necessity of charging infrastructure (R4):** The decision for trucking companies to adopt a new truck type partly depends on the availability of charging infrastructure. When more charging infrastructure is available the chance is higher that the trucking company will opt for a new truck type (Raofi et al., 2025). Similarly, the providers of charging infrastructure will see a better business case in opening a new charging station when there is sufficient demand from trucks of this type that have been adopted (Raofi et al., 2025)
- **Fleet dependent transport price (B5):** The first step in this balancing feedback loop is the price elasticity of *Hinterland truck transport [Mtkm]* to *Transport price per Mtkm for truck transport* (De Jong et al., 2010). When *Transport price per Mtkm for truck transport* increases, it decreases the demand for truck transport in the Port of Rotterdam because suppliers can divert to markets with cheaper transportation costs. Only when *Hinterland truck transport [Mtkm]* increases, will it instigate the addition of extra trucks through an increase of the *Hinterland truck fleet size*. This larger fleet results in a fleet with a higher *TCO truck fleet*, which reduces the *Transport price per Mtkm for truck transport*.
- **Price effect of decarbonization (FBL6):** The basis for this feedback loop is the price elasticity of *Hinterland truck transport [Mtkm]* to *Transport price per Mtkm for truck transport* (De Jong et al., 2010). When *Transport price per Mtkm for truck transport* increases, it decreases the demand for truck transport in the Port of Rotterdam because suppliers can divert to markets with cheaper transportation costs. Only when *Hinterland truck transport [Mtkm]* increases, will it instigate the addition of extra trucks through *Adoption of trucks with lower carbon capacity*. The sign of the feedback loop depends on whether *Adoption of trucks with lower carbon capacity* results in a fleet with a higher or lower TCO truck fleet, which depends on the affordability of the new truck types.

The feedback loops present in the system are predominantly reinforcing feedback loops. Four out of six are reinforcing feedback loops, with the possibility for *Price effect of decarbonization* to also be reinforcing. This abundance of reinforcing feedback loops shows potential for unstable system behaviour, if the reinforcing effects are not mitigated by the balancing feedback loops or system delays.

5.2.5. System delays

Delays are another typical characteristic of dynamic systems and appear in the causal loop diagram of Figure 5.1. The underlying mechanisms of the delays and their durations are as follows:

- **Robustness of transport market:** The price elasticity from (De Jong, 2010) for *Price per Mtkm for truck transport* does not have an immediate effect on trade volumes, tracked by *Hinterland truck transport[Mtkm]*. Existing trade relations that are reliant on Port of Rotterdam hinterland transport will not be severed immediately at the moment that the price becomes less competitive to other transport hubs and connected markets. There are ongoing contracts that need to be fulfilled and deals in competing markets to be completed, before the business can be moved. It is also common for demand of a certain good, in this case for truck hinterland transport in the Port of Rotterdam, to show a delayed reaction to price dynamics (Auping et al., 2012). Therefore, the

delay on the price elasticity effect is assumed to be 3 years based on the time it takes for contract renegotiations, operational adaptations and physical and logistical investments.

- **Truck ageing:** The truck fleet of the Port of Rotterdam consists of trucks of different ages. The age of a truck is a crucial factor for a trucking company for deciding the long-term strategy with the truck. As a truck ages, energy efficiency lowers and costly repairs might need to be performed. The trucking company will weigh its options - exporting, scrapping or continued use - based on a cost analysis. Only when the truck is exported or scrapped, an opportunity arises for the adoption of a new truck type. Thereby, the adoption of truck types with a lower carbon intensity of energy is slowed down because old trucks pose a sunk cost that will not be discarded easily. Therefore, an ageing chain that keeps track of the age of trucks in the Port of Rotterdam fleet shows the real-life delay that is typical for long-term operational truck planning.
- **Construction time of charging infrastructure:** The construction of a new charging station requires a lengthy process, encompassing several elements. Appointing a suitable location, obtaining the building permit and finding a contractor for the construction are all challenges, specifically in The Netherlands. Charging providers have indicated that the time required to build a new BET charging station is two years (Raofi et al., 2025). This construction period will also be taken for the construction of a charging station for FCETs, by lack of a concrete source. Since the supply of charging stations can not immediately respond to increased adoption of renewable trucks to service, this delay has to be part of the system dynamics model. However, charging providers also indicated to work with a planning horizon of five years, taking into account an extrapolation of the last three years of BET-adoption (Raofi et al., 2025). This future-oriented planning strategy mitigates part of the construction delay, but is not able to capture rapid growth during the construction period that is typical for the potentially rapidly emerging technologies in this study.

5.2.6. Dynamic hypotheses about system behaviour

The model that has been conceptualized in this section shows interesting dynamical features that allow for the formulation of dynamic hypotheses about its behaviour:

1. Chicken-and-egg problem for truck adoption and charging infrastructure:

Feedback loop *Necessity of charging infrastructure (R4)* shows a reinforcing feedback loop between lower-emission truck adoption and the construction of charging infrastructure aimed at facilitating these trucks. When both factors are abundantly present, these two factors can positively influence each other and lead to exponential growth of both lower-emission truck adoption and charging infrastructure. However, in the case of an emerging technology both are low. What happens is that in the absence of a dense enough network of charging stations, e-truck adoption stays low, which in turn lowers the demand for charging. The incentives for investing in the construction of charging infrastructure are diminished by the low demand for charging. In addition, a 2-year delay has been found for the construction of charging infrastructure. Neither the trucking company wants to act first and adopt a lower-emission truck, nor the charging infrastructure provider acts first by starting construction for charging stations, causing the chicken-and-egg problem (Raofi et al., 2025). Since the adoption of these new trucks is undesired to lower carbon emissions of truck hinterland transport, lower-emission truck adoption and charging infrastructure are captured in a vicious circle (Wolstenholme, 1990).

2. Exponential lower-emission truck adoption:

Two reinforcing feedback loops - *Word-of-mouth (R2)* and *R&D cycle (R3)* - are directly linked to lower-emission truck adoption. Therefore, it is hypothesized that once lower-emission truck adoption initiates, growth will develop exponentially.

3. Lower-emissions trucks leading to lower transport costs:

In the causal loop diagram it can be seen that the adoption of lower-emission trucks reduces the CO₂-emission and therefore the *Transport price per Mtkm for Hinterland truck transport*. However, this hypothesis depends on the sign of the *Price effect of decarbonization (FBL6)* feedback loop, which includes other TCO factors besides carbon emission tax.

The following model analysis forms an attempt to falsify these dynamic hypotheses (Auping et al., 2024).

5.3. Formulation

5.3.1. Model setup and settings

The model will be initialized in 2025 and run until 2050, resulting in a medium-term analysis of 25 years. The unit of time is years, since the most important model decisions - new truck adoption and charging infrastructure construction - take place yearly. The smallest time-step constant in the model is one year, for *Time in diesel age group*. According to Auping et al. (2024) the time-step for the model should be at least half of this smallest time-step. However, a smaller timestep of 0.125 has been chosen to further increase the accuracy of system delay representations, without runtime of the model simulations becoming too long.

Since the model makes use of MIN and MAX functions, derivatives of variables in the model can be discontinuous. This can lead to abrupt system changes. Due to this discontinuous model behaviour Euler has been chosen as an integration method, as is recommended by Auping et al. (2024).

Further information about the chosen parameter values can be found in Appendix C.

5.4. Sub-model formulation

5.4.1. Adoption of lower-emission trucks

[Structural overview of sub-model](#)

The sub-model of adoption of lower-emission trucks consists of multiple interacting sub-parts: ageing chains, adoption choice, new truck adoption and TCO calculation. In Figure 5.2 the ageing chains for the three different truck types - diesel, BET and FCET - are displayed. Also, the mechanism of deciding the probability of decision for a new truck type is displayed. This mechanism decides which ageing chain is entered.

Figure 5.3 shows the adoption of new truck adoption outside of the renewal cycle. Also, it shows the yearly TCO calculation that plays a role in the probability of adoption for different truck types.

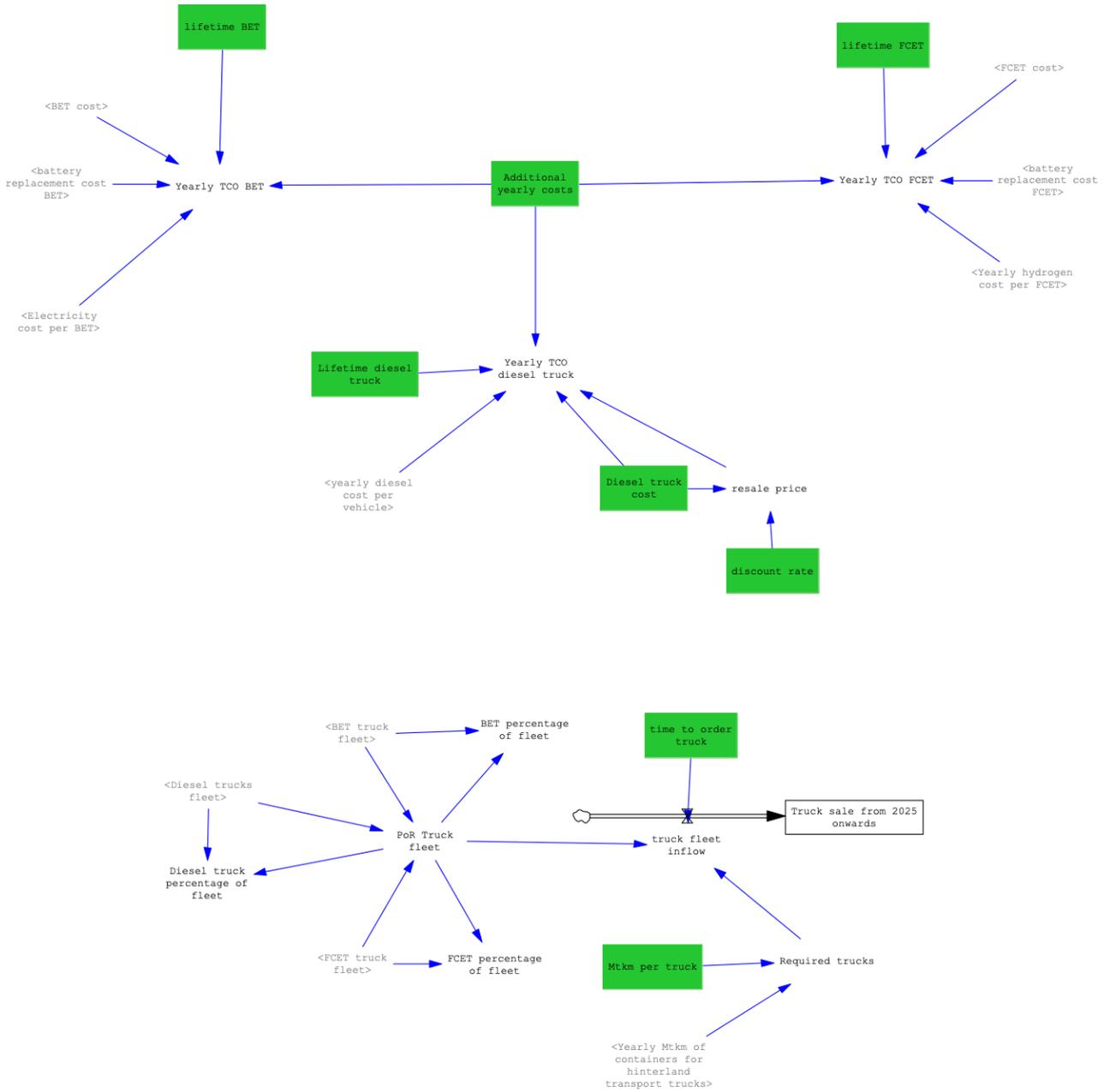


Figure 5.3: Sub-model adoption of lower-emission trucks: new truck adoption and yearly TCO calculation

Description of the sub-model

Central in the sub-model is the ageing of trucks in the Port of Rotterdam truck fleet, that decides at which moments during the model run decisions for fleet renewal are made. The ageing of trucks is implemented with an ageing chain, a standard structure in the field of system dynamics (Auping et al., 2024). The ageing chain is utilized to illustrate circumstances where the outflows of items in a stock and flow structure are age-dependent and allows for the simulation of changes (through inflows and outflows) of any intermediate stock of the aging chain structure (Ghisolfi et al., 2024). An example of an ageing chain specifically for trucks was present from earlier system dynamics research by Ghisolfi et

al. (2024). This ageing chain has been rebuilt for the three competing truck variations: BETs, FCETs and diesel trucks.

Transitions between the stocks of trucks of different age groups occur due to stocks containing a DELAY FIXED function. For the transition from BETs from the first age group to the second age group at age 7, the following function is used:

$$\text{BET 6 to 7} = \text{DELAY_FIXED} \left(\text{BET Adoption}, \text{BET Time in Age Group 1}, \frac{\text{BET}_{0-6 \text{ years old}}}{\text{BET Time in Age Group 1}} \right) \quad (5.1)$$

This DELAY FIXED indicates an infinite-order material delay, also known as a pipeline delay (Auping et al., 2024). The magnitude of the delay depends on the ageing chain, with the ageing chain of diesel trucks having been constructed with 1-year timesteps, while the ageing chains for BETs and FCETs contain two 6-year age groups with only one ageing step between them. This modelling choice has been made due to the different events that happen during the lifetime of these different truck types. For diesel trucks new trucks stem both from buying new truck models, as well as importing secondhand trucks (Bhoraskar & Mulder, 2023). This importing happens at different ages according to the specific energy hub under analysis. Furthermore, keeping track of the specific age of trucks can help in calculating the energy efficiency that can differ per age group, although a generalised energy efficiency is taken in this model. Thus, the ageing chain with 1-year timesteps allows for flexibility of applying the model to different contexts and for future research extensions.

This ageing chain for the truck fleet of Brazil by Ghisolfi et al. (2024) was adapted to the local context of the Port of Rotterdam. In Brazil, the average age of trucks is higher than in The Netherlands. In The Netherlands, tractor-trailer trucks are on average only 7.5 years old, so the ageing chain was shortened (Bhoraskar & Mulder, 2023). Also, the lifetime of a truck in the ageing chain from Ghisolfi et al. (2024) ended with scrappage, while for diesel tractor-trailer trucks in The Netherlands export is still an option when they exit their shorter ageing chain. The average age at which a diesel tractor-trailer truck is exported from The Netherlands is 8 years, which was taken as the final age stock in the ageing chain for diesel tractor-trailer trucks (Bhoraskar & Mulder, 2023). In the case that a diesel tractor-trailer truck is exported, a resale value is calculated based on a 7% yearly discount rate over the original purchase price (Noll et al., 2022). Tractor-trailer trucks enter the ageing chain at two different points, for they are purchased new but also a smaller percentage is imported at an average age of 5 years (Bhoraskar & Mulder, 2023). For BETs and FCETs the ageing chain finishes at a lifetime of 12 years, since one interviewee stated that producers of BETs and FCETs estimate the lifetime of their vehicles at 12 years [Interview 1]. This aligns with the regulation from the Municipality of Rotterdam that does not allow trucks older than 13 years to the Maasvlakte, the largest port area in the Port of Rotterdam (Municipality of Rotterdam, 2025). At 12 years, no resale value is calculated for BETs and FCETs, because that age requires costly replacement of battery and fuel-cell stack (Noll et al., 2022).

The sub-model replicates the choice between truck types based on the Cobb-Douglas function. The Cobb-Douglas utility function is a mathematical expression commonly used in economics to model consumer preferences and utility resulting from the consumption of products and services (Safarzyńska & van den Bergh, 2017). The utility of a product in the Cobb-Douglas function is based on different factors, while absence of one of the three factors results in zero utility (Raofi et al., 2025). In this research three factors — maturity, adoption rate and charging infrastructure availability - have been identified that when absent form barriers to the existence of any utility for the lower-emission truck types. The relative contribution from these factors to the Cobb-Douglas utility score can be integrated as weight in the formula. The weights stem from estimations by (Raofi et al., 2025), who has collected answers from truck adoption decision makers - trucking companies - and averaged their estimations. The highest weight is attributed to charging station availability at 0.45, then technology adoption rate with a weight of 0.4 and finally technology maturity with a weight of 0.15. The Cobb-Douglas equation for utility of BETs is shown in equation 5.2.

$$\text{Cobb Douglas BET} = \text{BET maturity}^{0.15} \cdot \text{Technology adoption rate BET}^{0.4} \cdot \text{Availability of electric charging station}^{0.45} \quad (5.2)$$

TCO is the most important factor underlying lower-emission truck adoption, as has been indicated in validation interviews. Therefore, it is included in this sub-model as *Yearly TCO*, consisting of purchase

price of that truck, yearly fuel costs and soon to be installed ETS2 carbon tax over the emissions of these fuels. Also, *additional yearly costs* specific for trucks in The Netherlands contribute to *Yearly TCO* and include relevant costs such as: Driver cost, tyre replacement, other maintenance & repair, tolls, insurance and vehicle taxes (Comité National Routier, n.d.). For BETs and FCETs battery swap is required after 6 years, leading to extra added cost during the lifetime of these truck types (Noll et al., 2022). The Cobb Douglas values are divided by the TCO, summed together, after which the fraction of the Cobb Douglas for that truck technology represents the preference for that truck in comparison to the other truck technologies. When trucks are exported or scrapped, the model creates new trucks according to the preferential values of the Cobb Douglas function.

Another factor included in the Cobb Douglas function for lower-emission truck adoption is adoption rate. When adoption rate in the model rises, there are more sales of that technology, from which a percentage can flow back and stimulate R&D for that technology. The maturity level at a particular level is in itself also a determining factor for truck sales. As a technology matures, it creates more confidence among the end consumer and there is going to be a positive effect on sales (Nieuwenhuijsen et al., 2018). As is widely known in marketing theory and practice, there are, of course, variations in adoption rates across the population. When a technology is more developed, a larger group of individuals follow the early adopters. Later on, after the technology has reached its full maturity, another segment of the population begins to use it. An S-shaped adoption rate is typically the outcome of this phased adoption (Nieuwenhuijsen et al., 2018).

The level of maturity also influences lower-emission truck adoption. Maturity has been quantified with a range from 0–100% (Nieuwenhuijsen et al., 2018). While it can be argued that a technology never reaches 100% maturity and can always improve further, the emerging technologies are compared with the fully-mature technology of internal combustion engine trucks that acts as a ceiling at 100%. With that reasoning, the current maturity of the diesel trucks is seen as the highest level of maturity that can be obtained, due its long-term reliability and performance in the transport sector. Since the emerging technologies aim to compete with the market of internal combustion engine trucks, this highest level of maturity that can be obtained forms a valid benchmark for full maturity. Additional maturity beyond 100%, for example by improved efficiency in internal combustion engines, is addressed in the sub-model by blending it more explicitly into other influenced factors that decide technology choice, such as the TCO. The growth curve of maturity follows an s-shaped curve. Initially, low sales generate low R&D budgets that can be spent on maturity improvement. When adoption is accelerating, the increased R&D budget will lead to a more rapidly developing maturity, that will slow down once the maturity level approaches the ceiling at 100%. That is because R&D typically focuses on the low hanging fruit first, efficiently utilizing its budget to improve the technology. When these 'quick fixes' have been implemented to significantly improve maturity, it becomes more difficult and less cost-efficient to improve the technology further towards full maturity.

Another important detail of this sub-model is that a LOOKUP function has been used to define the value of *Battery BET cost* and *Battery FCET cost* over time. The current price is 200 euro/kW, but due to expected improvements in production techniques expected to fall to 140 euro/kW in 2030 and 100 euro/kW in 2040 (Basma et al., 2021). The expected value for 2040 of 100 euro/kW is used for the completion of the runtime up until 2050, due to a lack of information on whether this decreasing battery cost will continue past 2040.

Inputs from other sub-models

Relations from the sub-model with other sub-models displayed in the causal loop diagram in Figure 5.1 have been formalized more explicitly. First of all, an increase in *Yearly Mtkm of containers for hinterland transport trucks* from the truck hinterland transport sub-model initiates the adoption of new trucks in this sub-model. Secondly, yearly energy source cost and CO₂-emissions tax are calculated per truck in the CO₂-emission from truck hinterland transport sub-model, and used in this sub-model to calculate the yearly TCO. Lastly, infrastructure availability for both FCETs and BETs stems from their respective sub-models and is used as input for the Cobb Douglas function in this sub-model.

Assumptions in sub-model

Initial number of trucks

The ageing chains for different truck types had to be initialized in the model. Because no accurate information is available for the aggregated fleet specifically driving for the Port of Rotterdam truck hinterland transport, an assumption was required. That was done by comparing Port of Rotterdam hinterland transport with total truck transport in The Netherlands. In 2015 Port of Rotterdam truck hinterland transport consisted of 13.7 Gtkm (Lechtenböhmer et al., 2018). Truck transport in The Netherlands consisted of 41.65 Gtkm (Statista, 2024). By taking the fraction ($13.7/41.65=0.33$) and multiplying it with the number of active tractor-trailers in The Netherlands, the truck fleet size used for Port of Rotterdam truck hinterland transport could be calculated. There are 81533 tractor-trailers active in The Netherlands (Statista, 2023), resulting in a fleet of 28000 tractor-trailers for Port of Rotterdam truck hinterland transport. Only 0.9% of this is a BET (European Automobile Manufacturers' Association (ACEA), 2025). Also, there will be 1000 initial FCET in 2025 due to HyTrucks plan between Rotterdam, Duisburg and Antwerp (Rotterdam Maritime Capital, 2022).

Initial maturity values

As mentioned in Section 4.2, maturity of diesel trucks is set as a ceiling with an initial value of 1, that acts as a constant and does not change throughout the runtime (Raofi et al., 2025). Due to the considerations in Section 4.2.1 and interview-based estimations with BET-producers from Raofi et al. (2025), the initial BET maturity value is set at 0.2. For FCET maturity an own assumption had to be made. Given the considerations in Section 4.2.2, it was deferred that maturity was lower than for BETs and set at 0.1.

5.4.2. CO₂-emission from truck hinterland transport

Structural overview of sub-model

The sub-model of adoption of lower-emission trucks consists of three lines, representing the different truck types under analysis. For these truck types, Well-to-Wheel CO₂-emissions and corresponding CO₂-emissions costs are calculated. The sub-model is displayed in Figure 5.4.

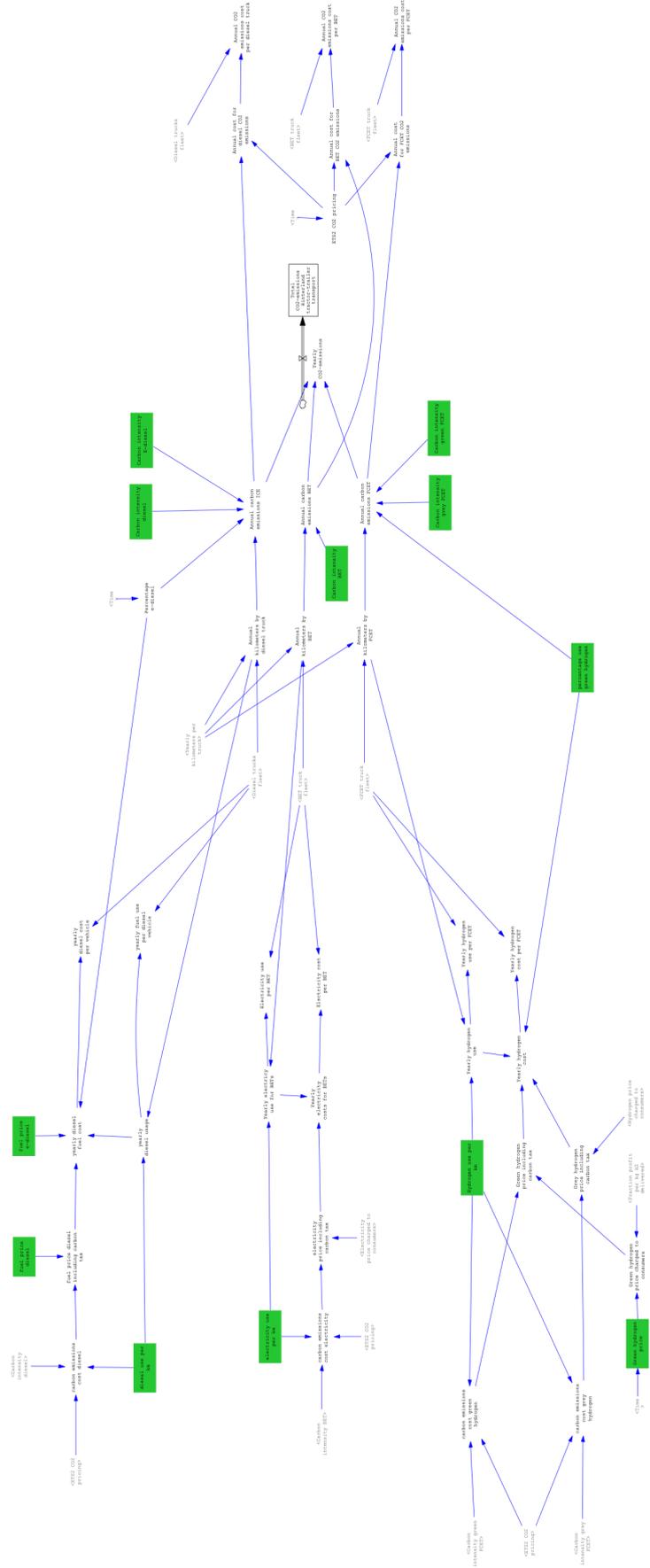


Figure 5.4: Sub-model CO₂-emission from truck hinterland transport

Description of the sub-model

The KPI of *Total CO₂ emissions of the hinterland truck transport* is calculated in one stock, collecting carbon emissions from all three truck type lines. That way, one measurement exists to track whether carbon reduction policies have had effect for the truck hinterland transport system as a whole. Carbon emissions for the three lines have been calculated with carbon intensities. No difference in carbon intensity based on the age of the truck has been implemented in the model. The carbon intensities from Table 4.3 have been recalculated to gCO₂/km values based on the energy contents of the energy sources used.

Also, two LOOKUP functions are present in the sub-model to simulate changing behaviour of the sub-system over time. A LOOKUP function has been used to decide the *Percentage of e-diesel* that is used in diesel trucks. The adoption of e-diesel is regulated by RED III EU Article 25, that sets out a dedicated binding sub-target for e-diesel of 1 % of transport energy consumption for 2030 (European Commission, 2023). Use of e-diesel beyond the mandatory consumption by law is not possible in the model, due to e-diesel not being price-competitive with normal diesel. Due to this stable percentage of e-diesel use, no dynamic behaviour due to an increasing adoption rate or maturity arises that could lead to growth of e-diesel use in the model. Since e-diesel is used in existing diesel trucks, it also makes sense to exclude this technology as an alternative with a relative attractiveness in comparison to lower-emission trucks, which is why e-diesel is only present in this sub-model.

Secondly, a LOOKUP function is present in the model that represents the increasing taxation on CO₂-emissions under the EU ETS2 scheme, part of the Renewable Energy Directive (RED) (European Commission, 2025). CO₂-emission prices will average 82 euros/tCO₂e in 2027 and 216 euros/tCO₂e (QC Intelligence, 2025).

Inputs from other sub-models

This sub-model operates mostly internally, without external influences. However, three inputs from other sub-models are required. First of all, *Yearly kilometers per truck* is calculated in the truck hinterland transport sub-model and influences annual kilometers for the fleets of different truck types. Secondly, up-to-date information about the size of truck fleets of different truck types is retrieved from the adoption of lower-emission trucks sub-model. Lastly, *Hydrogen price charged to consumers* is decided on the supply side in the charging infrastructure FCET sub-model, as is *Electricity price charged to consumers* in the charging infrastructure BET sub-model.

Assumptions in sub-model

Policy-dependent development of e-diesel

With only 40gCO₂e/MJ reduction for the early e-diesel, the carbon tax is only a price reduction of €0.1174/L with 82 euro/tCO₂e pricing under 2027 ETS2 CO₂-emission pricing. After 2027 the CO₂-emission pricing under ETS2 will increase, closing the price gap between diesel and e-diesel. However, the price of e-diesel is not expected to decrease enough to become competitive. Therefore, the adoption of e-diesel is dependent on binding targets set out by RED III EU Article 25.

No use of green hydrogen for FCETs

With the projected high green hydrogen prices up until 2050 (PBL Netherlands Environmental Assessment Agency, 2024; TNO, 2024), it will not become price-competitive with grey hydrogen for FCETs. This upholds if increasing ETS2-pricing, which increases the price of the higher CO₂-emitting grey hydrogen, is included. Therefore, the model assumes that trucking companies striving for cost-optimization will opt for grey hydrogen, excluding the use of green hydrogen for FCETs.

Zero carbon intensity for BET

In Table 4.2 a carbon intensity of 93.75 gCO₂e/MJ was provided for BETs, putting the carbon intensity of this lower-emission truck type at a relatively similar number to that of diesel and grey hydrogen using FCETs (Giuliano et al., 2021). However, this carbon intensity was based on electricity production from a wide variety of production methods, also polluting ways of electricity production such as coal. For the Port of Rotterdam, a large increase in wind energy is expected. The *Energy source availability* sub-model also shows that BETs only use a very minor factor of this green electricity in the future, in the range of 0.2%. Therefore, it can be assumed that BETs performing hinterland transport for the

Port of Rotterdam can run on renewable energy, leading to the assumption of a carbon intensity of 0 gCO₂e/MJ for this truck type. Residual grid CO₂-emissions caused by grid balancing by fossil-fuel producing actors during peak green electricity supply are acknowledged, but not considered.

5.4.3. Charging Infrastructure BET and FCET

Structural overview of sub-model

The sub-models for charging infrastructure describe the market for the operation of charging stations. Since this market is modelled similarly for BETs and FCETs, the individual sub-models are discussed jointly in this section, based on examples from the BET charging infrastructure sub-model. The sub-model consists of two sub-parts. First, the mechanism of the investment decision is displayed in Figure 5.5. When the investment decision is taken, the construction process of the charging station commences. The construction process of a charging station is displayed in Figure 5.6.

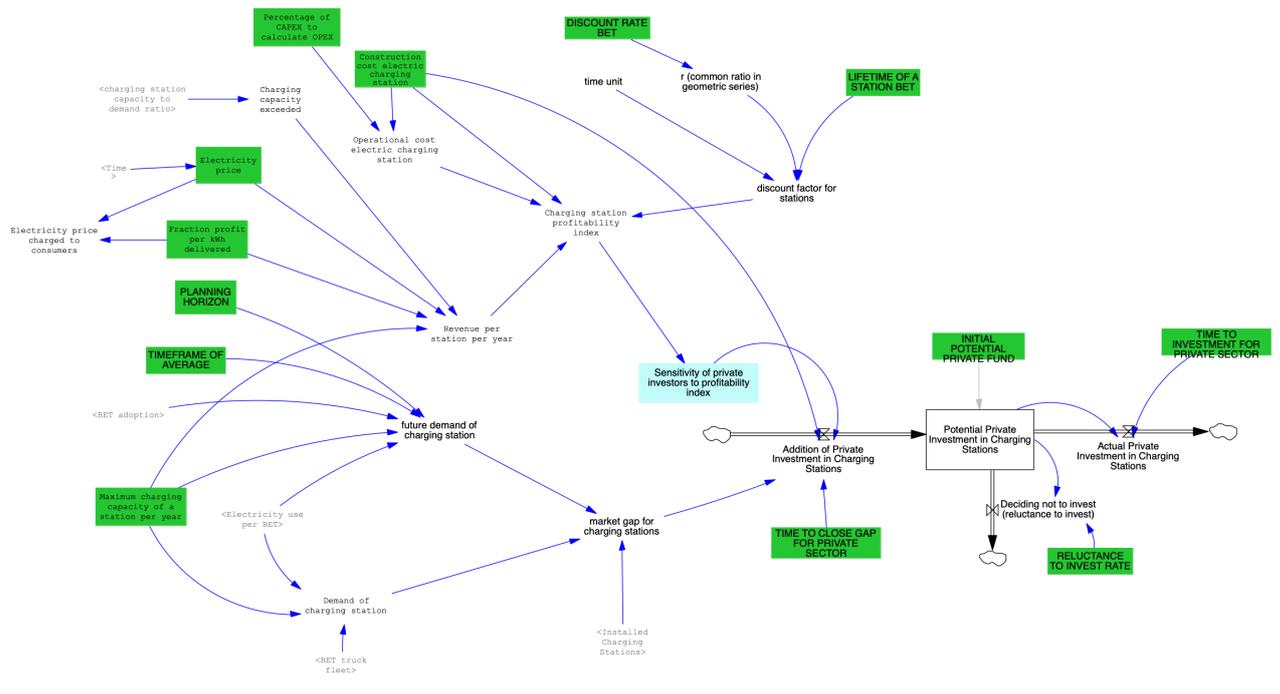


Figure 5.5: Sub-model charging infrastructure: Investment decision leading to the construction of a BET charging station

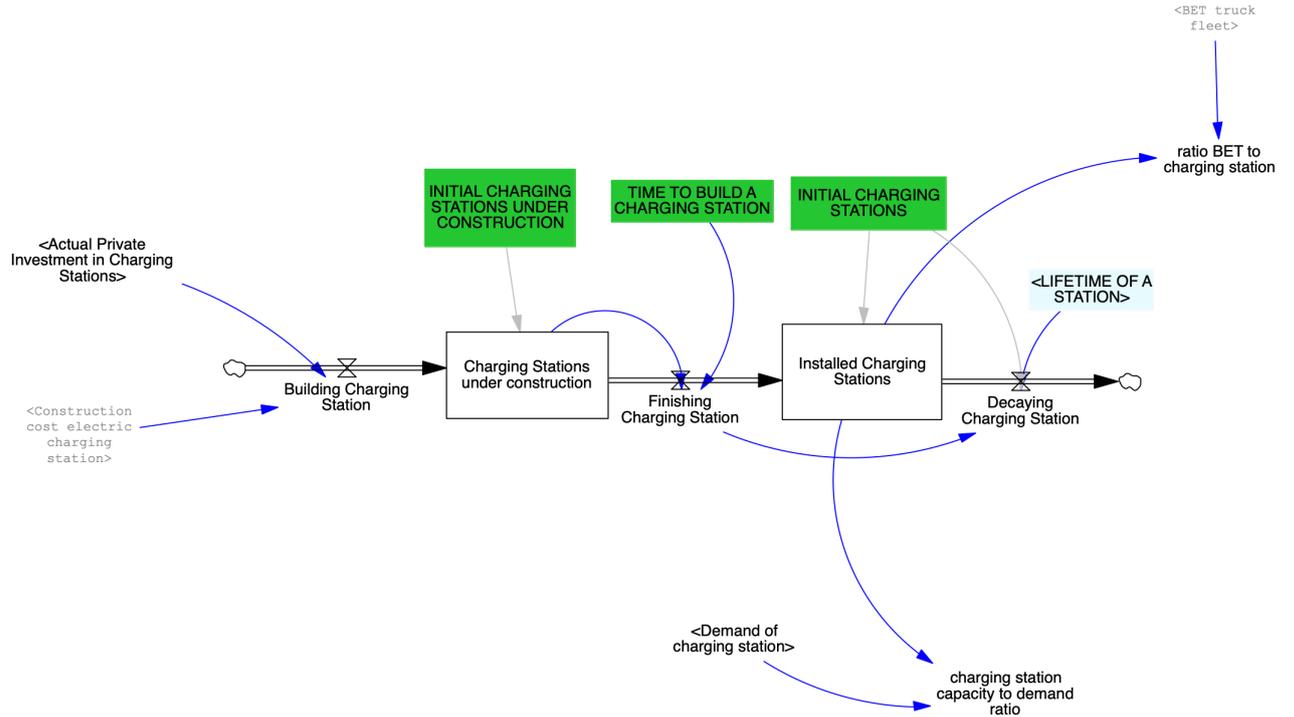


Figure 5.6: Sub-model charging infrastructure: Construction process

Description of the sub-model

The key performance indicator in this sub-model is the number of *Installed charging stations*, which is operationalized as the last stock in the sub-model. Charging stations are in operation during the period that they reside in this stock. At the end of their lifetime a charging station is expected to decay and taken out of operation, as is represented by an outgoing flow from the stock.

The sub-model is based on a model from Raoofi et al. (2025), but parameter values have been adapted to the local environment of the Port of Rotterdam truck hinterland transport. Also, the model is altered to include solely a private sector decision, without including public subsidies and other public interventions. That way, it can be studied whether the functioning of the market mechanism of charging infrastructure for BETs and FCETs is autonomous. This market mechanism produces very different behaviour for BETs and FCETs, due to the *Construction cost electric charging station* being much higher for a FCET charging station than a BET charging station. Since OPEX is calculated by taking *Percentage of CAPEX to calculate OPEX*, OPEX is significantly higher for FCET charging stations. In order to still present a profitable business case to FCET charging station operators, and mimic public subsidies that are not regarded in the sub-model, the *Fraction profit per energy unit delivered* has been increased for FCET charging stations.

To mimic the strategic planning of charging infrastructure operators, that want to recognize demand early so that the construction process can commence, the model makes use of a *future demand of charging station*. This variable is operationalised as follows:

$$\text{Future demand of charging station} = \frac{\text{SMOOTH}(\text{BET adoption, Timeframe of average}) \cdot \text{Electricity use per BET} \cdot \text{Planning horizon}}{\text{Maximum charging capacity per station per year}} \quad (5.3)$$

The use of a SMOOTH function allows for the calculation of the moving average of future demand for charging stations. In this calculation the average of the previous years is taken as a stable measure of the current demand, while this demand is regarded for five years in the future to assess whether there is a market gap.

The construction process is implemented with a delay function. Once the investment decision has been taken a charging station enters the stock of *Charging stations under construction*. The outgoing flow from this stock contains the following delay:

$$\text{Finishing charging station} = \frac{\text{Charging stations under construction}}{\text{Time to build a charging station}} \quad (5.4)$$

The delay is a first-order material delay of 2 years. The order is low to represent the non-rigid transition of a charging station under construction to a charging station that is installed. This aligns with real-world planning time deviations of construction projects.

For *Electricity price* a LOOKUP function has been used that takes into account the development of the electricity market within the runtime of the model. Electricity price is influenced by its various production methods in the energy mix. Where the price for carbon intensive energy production methods such as from coal and gas will increase due to increased carbon emissions tax under the ETS2 scheme, oversupply of renewable electricity can also lead to negative electricity prices at peak hours (Schmitt et al., 2024). These mechanisms are predicted to balance each other and keep electricity prices relatively stable. Up to 2030 an electricity price of 0.069 euro/kWh is expected, with a rise to 0.078 euro/kWh by 2050 that is assumed to take place linearly. Since depot charging is utilized in this study, it is expected that these real electricity prices can be offered to BET-users. The only addition is the *Fraction profit per kWh delivered* that has to be charged by BET charging station operators in order to create a viable business case. The model has been tested in order to find the right value, which has been found at 0.5.

Inputs from other sub-models

This sub-model requires inputs from other sub-models to construct the investment decision in charging stations. First of all, to calculate the *market gap for charging stations* up-to-date information is required about *BET adoption* and *BET truck fleet* from the Adoption of lower-emission trucks sub-model, as well as *Electricity use per BET* from the CO₂-emission from truck hinterland transport sub-model. Furthermore, *Electricity price* from the CO₂-emission from truck hinterland transport sub-model decides what the fraction of profit per energy unit is and thereby aids in calculating the *Revenue per station per year*.

Assumptions in sub-model

For this sub-model no assumptions have been made by the researcher. Parameter values stem from literature or are based on assumptions in literature.

5.4.4. Truck hinterland transport

Structural overview of sub-model

The truck hinterland transport sub-model brings together the hinterland truck cargo throughput and the existing truck fleet. The sub-model uses both factors to calculate relevant hinterland transport parameters at the macro-level and micro-level, that are used as input for other sub-models. Also, the sub-model show the attractiveness as a trade partner of the Port of Rotterdam based on its transport price for truck hinterland transport.

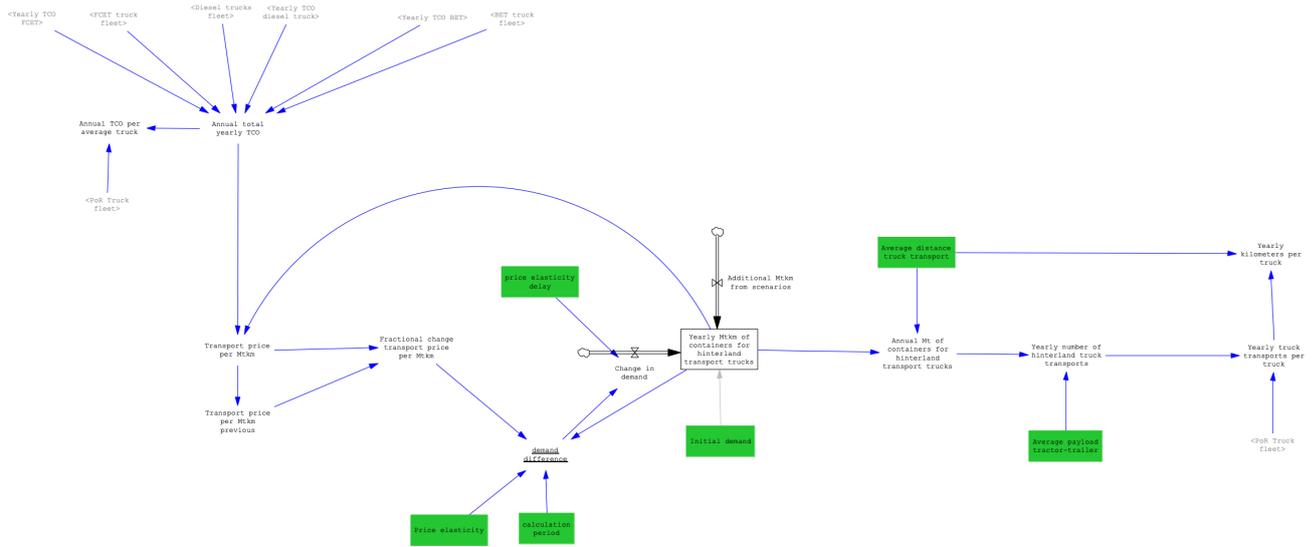


Figure 5.7: Sub-model truck hinterland transport

Description of the sub-model

The sub-model calculates *Annual total yearly TCO* for the whole Port of Rotterdam truck fleet, in order to calculate *Transport price per Mtkm*. The *Yearly Mtkm of containers for hinterland transport trucks* has to be performed by this truck fleet, so the cost of operating this fleet is at the base of calculating the transport price that truck operators ask for transporting containers for Port of Rotterdam truck hinterland transport. This *Transport price per Mtkm* forms the key performance indicator present in this sub-model. An increase in *Annual total yearly TCO* leads to an increase of the *Transport price per Mtkm*. This increase in *Annual total yearly TCO* can be caused by an increase in the truck fleet size, or higher yearly TCO of newly adopted truck types. An increase in the *Yearly Mtkm of containers for hinterland transport trucks* will lead to a decrease of *Transport price per Mtkm*, since trucks are able to spread out their yearly TCO over more kilometers, while only yearly fuel costs increase the TCO in case of more driven kilometers. This increase remains until the market demand gap for hinterland truck transport is fulfilled by the adoption of new truck types to bring back the *Yearly kilometers per truck* to its original level.

Changing *Transport price per Mtkm* triggers the price elasticity of *Hinterland truck transport [Mtkm]* to *Transport price per Mtkm for truck transport* (De Jong et al., 2010). When *Transport price per Mtkm for truck transport* increases, it negatively influences the demand for truck transport in the Port of Rotterdam because suppliers can divert to markets with cheaper transportation costs. This long-term price elasticity is characterized by a delay and formalized in the following way:

$$\text{Change in demand} = \text{DELAY_INFORMATION}(\text{Demand difference}, \text{Price elasticity delay}, 0) \quad (5.5)$$

The delay type is informational, because it takes suppliers time to react to this price incentive and rewire the physical flow of their transport goods to other transportation hubs and markets. The delay on the price elasticity effect is set at 3 years based on the time it takes for contract renegotiations, operational adaptations and physical and logistical investments. *Demand difference* is calculated taking into account *Transport price per Mtkm* for the current year of the runtime and the previous year, as well as a price elasticity value of -1.0. This value of -1.0 consists of -0.4 in mode change and -0.6 in reduced transport demand (De Jong et al., 2010). Mode change is a switch to inland waterways or train, which means that the cargo is still handled by Port of Rotterdam as part of their hinterland transport. However, a mode change entails reduced truck hinterland transport and therefore the cargo throughput leaves the system under analysis. This price elasticity also triggers three feedback loops: Transport price attractiveness (R1), Fleet dependent transport price (B5) and Price effect of decarbonization (FBL6). Given the different effects - reinforcing or balancing - of these feedback loops it is difficult to trace

the individual effects of these feedback loops. However, it does make the truck hinterland transport sub-model crucial in the overarching system under analysis.

Inputs from other sub-models

The truck hinterland transport sub-model uses up-to-date truck fleet size of the different technologies and their corresponding TCO-values from the *Adoption of lower-emission trucks* sub-model. Also, the number for the entire *PoR truck fleet* from the *Adoption of lower-emission trucks* sub-model is utilized to calculate values per truck, that are required elsewhere in the model.

Assumptions in sub-model

Tractor-trailer trucks weigh on average 27485 kg, divided over its own weight of 15729 kg and 11756 kg of average payload (Ligterink & TNO, 2015). The modelling choice has been taken to use an average for payload, instead of taking into account variations in payload for different transports. Therefore, varying energy efficiency levels that are intertwined with payload differences are not taken into account. In 2015 *Annual Mt of containers for hinterland transport trucks* was 106 Mt, which is taken as the initial value in this model (Lechtenböhmer et al., 2018). *Average distance truck transport* is 129km (Lechtenböhmer et al., 2018). Given that the cargo is transported for this average of 129km, *Yearly Mtkm of containers for hinterland transport trucks* consists of a total of 13.7 Gtkm. The *Yearly number of hinterland truck transports* is calculated the following way:

$$\text{Yearly number of hinterland truck transports} = \frac{\text{Tonne-km}}{\text{Load per truck} \times \text{Distance}} = \frac{13.7 \times 10^9}{11,756 \times 129} \approx 9,034,096 \text{ drives} \quad (5.6)$$

This number of drives is evenly divided over the trucks present in the Port of Rotterdam truck fleet, resulting in the *Yearly truck transports per truck*. *Yearly truck transports per truck* is multiplied by the *Average distance truck transport* to generate *Yearly kilometers per truck*. The initial result is 40.562 km/year. This is close to 69018 km yearly average for tractor-trailers (CBS, 2024), besides trucks performing drives outside of hinterland transport as well. Therefore, the value is assumed to be reasonable for the purpose of this model.

5.4.5. Energy source availability

Structural overview of sub-model

This sub-model links newly adopted carbon intensity of energy reducing technologies and the use of their respective energy sources, to the availability of these energy sources in the Port of Rotterdam environment. The sub-model is displayed in Figure 5.8

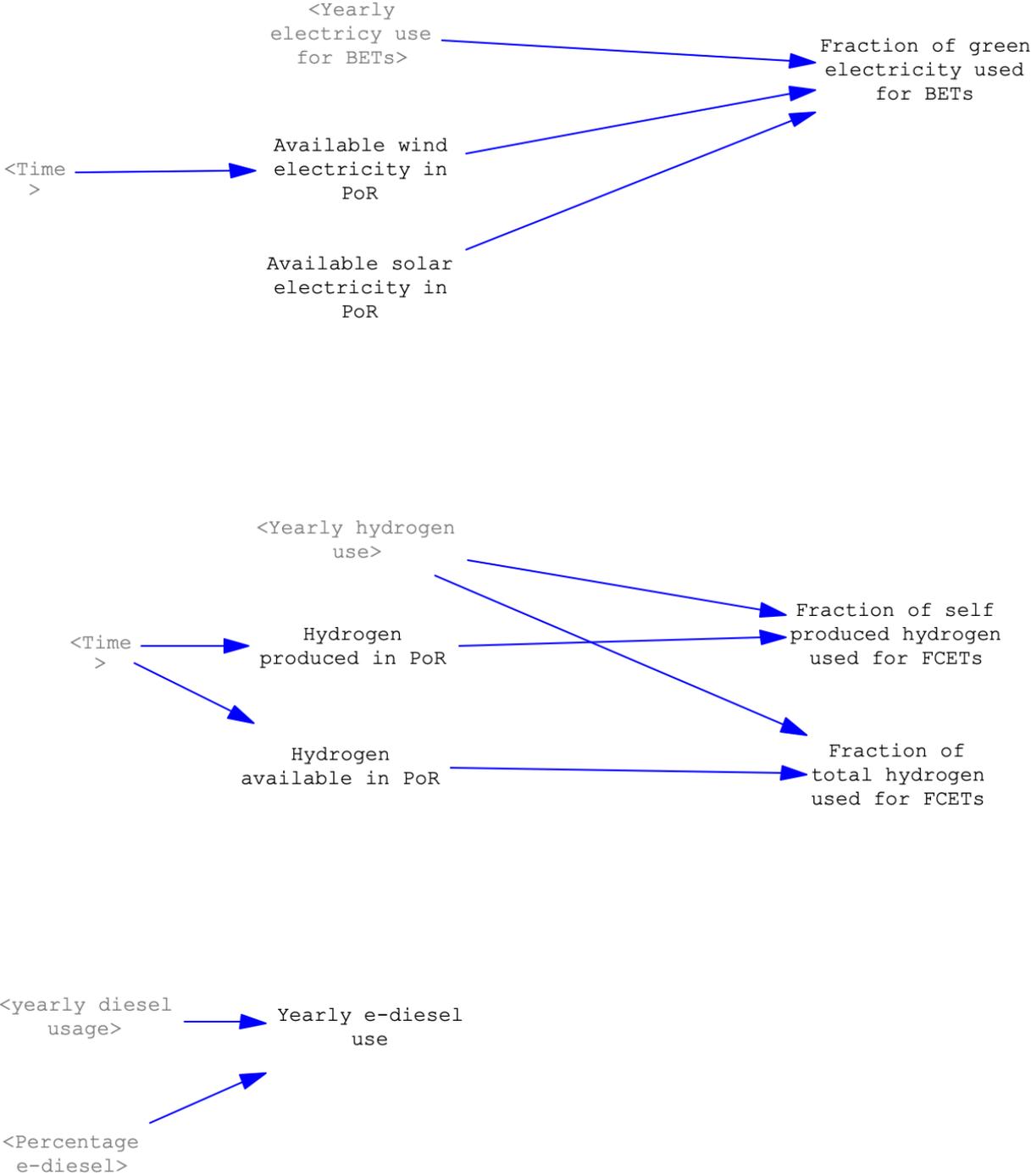


Figure 5.8: Sub-model energy source availability

Description of the sub-model

Fractions of the total supply of energy sources are calculated, to understand how large the burden of lower-emission technologies in hinterland truck transport is on the total CO₂ emission-reduction effort that is performed in the Port of Rotterdam. This is done for *Fraction of green electricity used for BETs* and *Fraction of total hydrogen used for FCETs*, the two key performance showcasing the relevant output of this sub-model. The Port of Rotterdam is besides an energy hub also an industrial cluster, in which different sectors have sustainable targets that require the use of renewable energy sources. Therefore, the truck transport sector is competing with other sectors for these energy sources, making it meaningful to get an understanding of what quantities of energy sources would be required for enabling the transition to carbon intensity of energy reducing technologies for truck hinterland transport.

Relations with other sub-models

Yearly use of the different energy sources is derived from the CO₂-emission from truck hinterland transport sub-model. Apart from that, the sub-model is small but performs its function to calculate two system KPIs required to measure energy source availability.

Assumptions in sub-model

It is assumed in this sub-model that current energy source supply is fully utilized by current operations. Therefore, the sustainable transition of different industries in the energy hub has to occur based on the creation of new energy source supply. Port of Rotterdam plans for increasing energy source supply have been used for this. Plans for increasing electricity supply to fuel BETs is based on the strategy of creating more wind-powered electricity. It is assumed that the electricity grid is capable of handling this increased use, with Dutch net operator Tennet recognizing the strategic importance of the Port of Rotterdam energy hub. Plans for the creation of more hydrogen supply in the Port of Rotterdam for a large part lean on import, but the small amount that is expected to be produced locally is also implemented in the model. In this model it is expected that these plans for increasing energy source supply are realized.

5.5. Evaluation

To evaluate the formulated model a series of evaluative steps is described in the following sub-sections. First of all, the strengths and weaknesses that have arisen from thorough verification and validation are named. Secondly, the model results are interpreted. Lastly, scenario analysis is performed to analyse the robustness of model behaviour.

5.5.1. Strengths and weaknesses of the model

To guarantee both technical accuracy and behavioural plausibility, the model was thoroughly validated and verified. Verification outcomes showed that the model was implemented with proper coding, dimensional consistency, and no numerical errors, all in line with the conceptual design. Components were verified against the original design logic and equations were examined methodically, as is reported in Appendix D.1.

Face validation by experts by the use of the boundary-adequacy test, structure-verification test and parameter-verification test confirmed the model's structural sufficiency. The boundary-adequacy test confirmed the belief that the different sub-models are all relevant factors for lower-emission truck adoption. It also confirmed the usefulness of studying the truck fleet specifically for an energy hub such as the Port of Rotterdam, for a medium-term timeframe up until 2050. Answers to questions posed in the structure-verification test established that feedback loops, like the Price effect of decarbonization (FBL6), effectively depict causal mechanisms in the real world. In the parameter-verification test interviewed experts agreed on key parameter assumptions, including negative estimations for green hydrogen pricing and the relative significance of maturity, adoption rate, and charging station availability in technological adoption. This alignment increases trust in the internal reasoning and parameterization of the model.

Extreme conditions tests in Appendix D.2.4 showed realistic model responses in improbable but diagnostic situations. Changes in diesel's carbon intensity had no drastic effect on adoption patterns, which

is in line with the carbon tax's relative contribution to total cost of ownership (TCO) for the transportation segment under study. On the other hand, although not to the degree of attaining full fleet dominance, changes in BET lifetime had a considerable impact on BET adoption, suggesting that yearly TCO is one of the driving variables for adoption. These results demonstrate that the model is not unduly sensitive to a single cost component, but rather accurately depicts multi-factor adoption dynamics.

Sensitivity analyses provided additional insight into the behaviour of the model, as shown in Appendix D.2.5. Due in great part to balancing feedback effects, multivariate study showed that operational KPIs (transport price per Mtkm, total CO₂ emissions hinterland tractor-trailer transport) are comparatively insensitive to parameter modification. However, due to the earlier development of BET technology compared to FCETs, adoption-related variables for FCETs showed stronger sensitivity, especially in the deployment of charging infrastructure. The implementation of charging stations and the adoption of BET were significantly impacted by the univariate sensitivity analysis of electricity prices, which were found to be a high-uncertainty parameter. With a larger increase in FCET uptake than the BET loss, higher electricity prices disproportionately decreased BET adoption. This underscores the correct functioning feedback loops Word-of-mouth (R2) and R&D cycle (R3) that increasingly reinforce FCET adoption once a market foothold is established.

In conclusion, the model has confirmed structural realism, accurate technological implementation, stability of important outputs under parameter uncertainty, and capacity to replicate intricate feedback-driven adoption patterns are among its overall strong points. Weaknesses include reliance on assumptions about future technological costs and infrastructure availability that are inherently unclear, as well as not taking into account less mature technologies that may play a crucial role in the medium-term timeframe up until 2050. The verification and validation procedure confirms the model's appropriateness for policy exploration in the specified environment, even if these constraints should be taken into account when interpreting the results.

5.5.2. Interpretation of model results

The validated system dynamics model produces results that can be interpreted in the light of its internal functioning. In this section, the development of key performance indicator values is interpreted over the running time of the model, initiated according to the initial values from Appendix C.

The first key performance indicators, *BET percentage of truck fleet* and *FCET percentage of truck fleet*, show the adoption pace of these lower-emission truck types. *BET percentage of truck fleet* is portrayed in Figure 5.9a, which shows an s-shaped growth curve that commences rapidly. With only a low number of initial BETs adoption rate is low, but due its initial higher maturity level feedback loop R&D cycle (R3) helps the adoption of BETs develop. Furthermore, ETS2 carbon taxation from 2027 on favours BETs, the least polluting truck type per kilometer. Lastly, decreasing battery costs for the large BET-batteries from 2030 on help increase the attractiveness of BETs in comparison to other truck types. Around 2040, the growth curve flattens as maturity increases become more costly and fiercer competition is experienced from FCETs.

In Figure 5.9b the growth curve of *FCET percentage of truck fleet* is portrayed. It shows an adoption rate that is less steep than for BETs, which also results in a lower percentage of fleet in 2050. This likely occurs because reinforcing feedback loops R&D cycle (R3) and Word-of-mouth (R2) are triggered to a lesser extent. Yearly TCO is the lowest for FCETs, remaining relatively stable throughout the runtime due to a decrease in battery cost and an increase in ETS2 carbon taxation on the continued use of grey hydrogen.

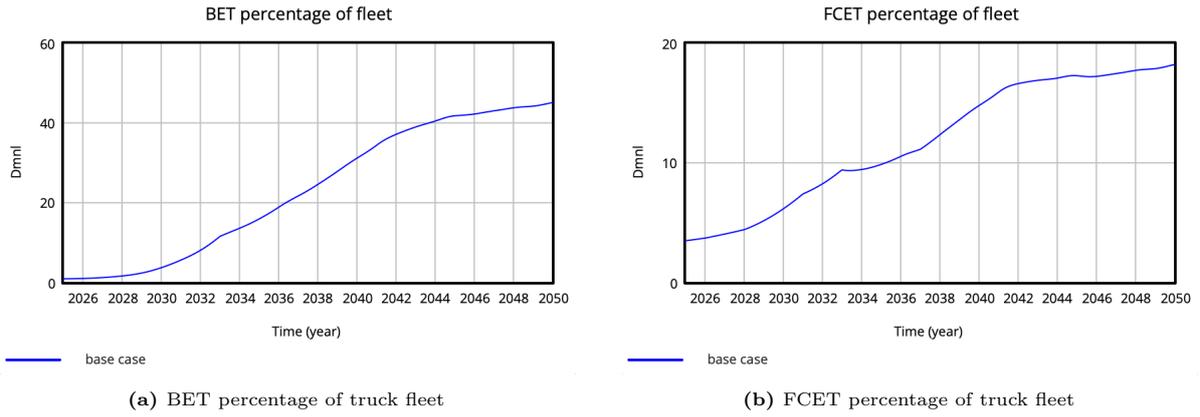


Figure 5.9: Model results of first two KPIs

A large limitation for adoption of FCETs is caused by another KPI, *Installed hydrogen charging stations*. In Figure 5.10b it is shown that in 2050 only 54 FCET charging stations are installed, which results in a 46% *Hydrogen charging station capacity to demand ratio*. This reluctance to invest in FCET charging stations stems from the high operational costs of these stations. In order to initiate FCET charging construction a high *Fraction profit per kg H2 delivered* has been used in the model. However, *Maximum charging capacity of a hydrogen station per year* remains low so this profit margin can not be earned over large volumes of H2. The *Hydrogen charging station profitability index* is only 1.24, meaning that only the least risk-averse investors decide to construct a FCET charging station. Therefore, supply of FCET charging stations stays behind, resulting in a low contribution of this factor to the Cobb Douglas function, thereby slowing down FCET adoption.

As for the construction of BET charging stations, *Installed charging stations* in Figure 5.10a shows a more attractive investment environment. Even with a low *Fraction profit per kWh delivered*, the *Revenue per station per year* is large enough to exceed yearly OPEX, making the operation of a BET charging station a profitable investment choice for investors. So attractive, that an overestimation of the demand also leads to an oversupply of *Installed charging stations*. Around 2035, when adoption of BETs is occurring at its highest velocity, this growing demand is extrapolated for the 5-year *Planning horizon*. This leads to an explosive increase in the number of *Installed charging stations*, caused by many investors jumping the gun and opening a BET charging station. As many investors take this investment decision simultaneously, competition arises and the market is oversupplied. This leads to a temporary ceiling being reached around 2040, during which the *Market gap for charging stations* is 0 and no new BET charging stations are installed. As the *BET percentage of fleet* continues to increase, although at a lower pace from 2045 as can be seen in Figure 5.10b, operation of a BET charging station becomes attractive for investors again.

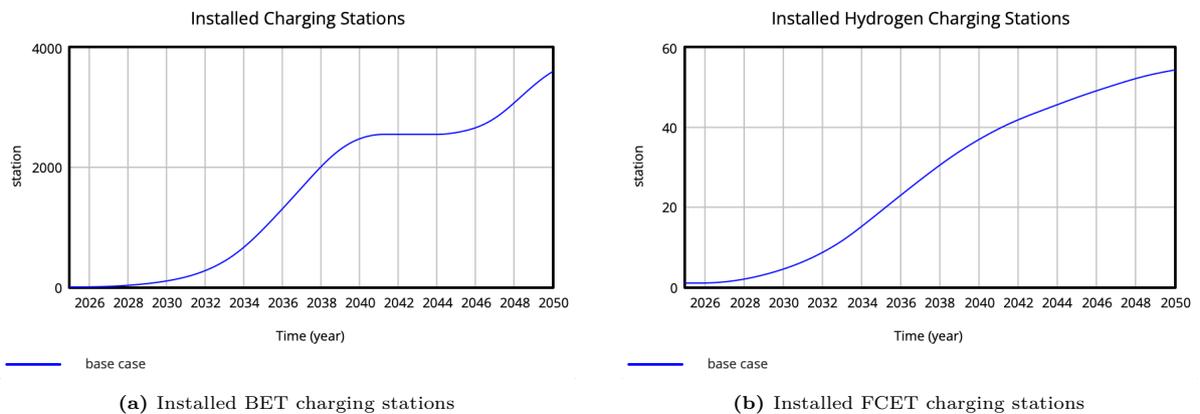


Figure 5.10: Model results of second two KPIs

Whether this transition to lower-emission trucks can be sustained by the required energy sources available in the Port of Rotterdam, is measured with the KPIs *Fraction of green electricity used for BETs* and *Fraction of total hydrogen used for FCETs*. From Figure 5.11a it can be deduced that the *Fraction of green electricity used for BETs* remains relatively stable throughout the runtime of the model. Apparently, the increase in available wind energy and the extra electricity required for the growing number of BETs balance each other out. Only in the first year of the runtime, before new wind electricity capacity is starting to be added, the *Fraction of green electricity used for BETs* is higher. However, throughout the whole runtime the *Fraction of green electricity used for BETs* is below 1%, which can be qualified as a low fraction, leaving enough green electricity for the decarbonization of other business segments of the Port of Rotterdam ecosystem.

From Figure 5.11b it can be seen that the *Fraction of total hydrogen used for FCETs* is characterized by a rapid rise in the initial stages of the run time. That is due to the rising number of FCETs in the Port of Rotterdam truck fleet, while increased *Hydrogen available in PoR* is only planned from 2030 on. Beyond 2030, the *Fraction of total hydrogen used for FCETs* keeps decreasing, meaning that the increase in hydrogen supply is larger than the increase in hydrogen use by newly-adopted FCETs.

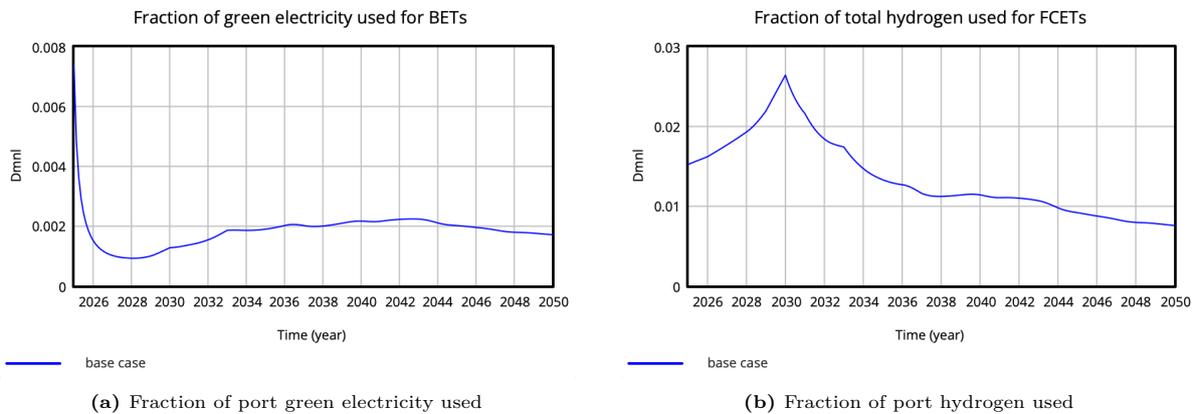


Figure 5.11: Model results of third two KPIs

The next KPI, *Total CO₂-emissions of truck hinterland transport* shows a slightly declining curve in Figure 5.12a. The decline is due to the increasing fleet percentages of lower-emission trucks, BETs and FCETs. However, the decline is only small because the use of green hydrogen in FCETs was deemed not possible due to its price-competition with cheaper grey hydrogen. Therefore, adopted FCETs drive only on grey hydrogen, an energy source with a large carbon intensity. By the adoption of lower-emission trucks, *Annual carbon emissions ICE* have been reduced by 700 million kilograms, but lower-emission trucks have partly undone this emission-reduction by adding an additional 189 million kilograms of CO₂ on a yearly basis.

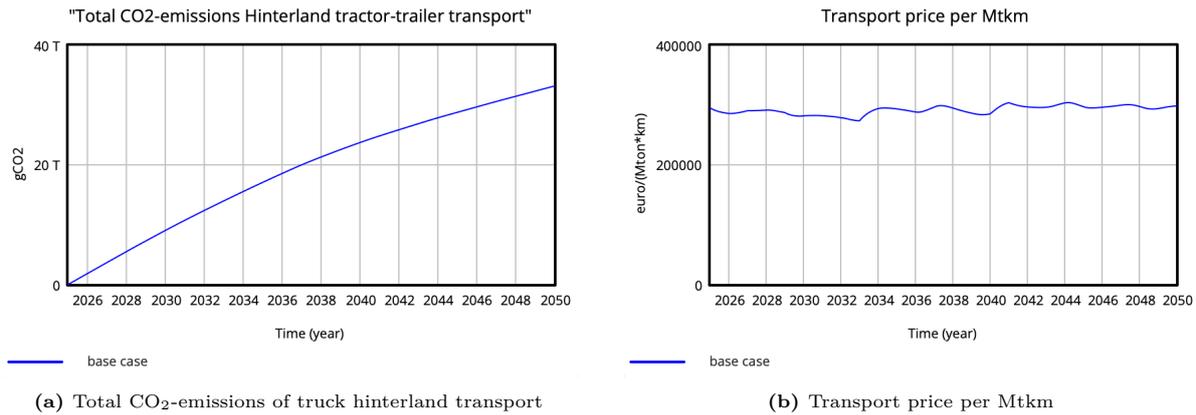


Figure 5.12: Model results of fourth two KPIs

The final key performance indicator, *Transport price per Mtkm* has remained relatively stable throughout the runtime. This is visible in Figure 5.12b. Deviations from the average are only small, likely due to the strength of balancing feedback loop Fleet dependent transport price (B5). A strong positive deviation can be seen around 2034, which is when increased ETS2 carbon-pricing lead to an increase in TCO for diesel trucks and FCETs. Also, that is when adoption of BETs occurs at the highest pace, with BETs being the truck type with the highest *Yearly TCO BET*. Otherwise the feedback loop Price effect of decarbonization (FBL6) is not clearly visible in the model results.

5.5.3. Scenario analysis

Explanation of scenarios

The problem of CO₂-emissions from truck hinterland transport of the Port of Rotterdam was identified in the light of an expected increase of container transport (Lechtenböhmer et al., 2018). Since a third of this container hinterland transport is executed by tractor-trailer trucks (Lechtenböhmer et al., 2018), an increase in container transport requires a larger truck fleet which leads to more CO₂-emissions. Including the future container-throughput in the model in the form of univariate scenarios therefore generates a broader bandwidth of system behaviour, which is the objective of scenario analysis (Auping et al., 2024). This broader bandwidth includes effects on the adoption of lower-emission truck types in the model, which makes it an interesting addition in order to study these adoption dynamics in more detail.

A rather general estimation has been made by Lechtenböhmer et al. (2018), that predicts that in two decarbonization scenarios total hinterland container transport will rise from 140 Mt to 212 Mt. Since 106 Mt out of the initial 140 Mt of containers was transported by truck - although transported for a shorter distance so only accounting to one third of total Gtkm of container hinterland transport - a fraction of 0.76 of total hinterland container freight is transported by trucks. Therefore, applying the fraction to the increase to 212 Mt would imply a rise in truck hinterland transport to about 160 Mt (Lechtenböhmer et al., 2018).

Besides this one-sided simulation, with an equal amount of container transport weight in two scenarios, more elaborate scenarios have been developed by the Port of Rotterdam Authority. In preparation for 2050, the Port of Rotterdam Authority has presented four thorough worldwide scenarios, that will be used for the scenario analysis of this research (Port of Rotterdam Authority, 2021). The four scenarios and their main drivers are described in more detail in Appendix E. The four scenarios are:

- Connected deep green
- Regional well-being
- Protective markets
- Wake-up call

All of these four scenarios represent an increase in the container cargo volume transported by trucks, even those scenarios in which world trade is not flowing freely. In the model this can be modelled as an increase in the central stock of *Yearly Mtkm of containers for hinterland transport trucks*, after

multiplication with the *Average distance truck transport* of 129 km. *Yearly Mtkm of containers for hinterland transport trucks* is initialized at 13.700 Mtkm, and only shows slight and balanced deviations during the runtime. Therefore, the additional Mtkm of truck hinterland transport projected by the scenarios can be implemented by creating an extra in-flow to the stock that contains the difference between the scenario value and the base case value of 106 Mt. Deviations in *Yearly Mtkm of containers for hinterland transport trucks* due to internal model behaviour will therefore not be influenced directly, which would reduce behaviour that the model naturally produces. Growth of container throughput volume in the scenarios is assumed to be linear, allowing for the calculation of an increase per year. The setup for the scenario analysis is represented by Table 5.1.

Scenario	Container volume [Mt]	Mtkm	Mtkm increase	Mtkm increase per year
Connected deep green	223	28.767	15.067	603
Regional well-being	176	22.704	9.004	360
Protective markets	134	17.286	3.586	143
Wake-up call	182	23.478	9.778	391

Table 5.1: Calculation of Mtkm input values for scenario analysis

Scenario analysis results

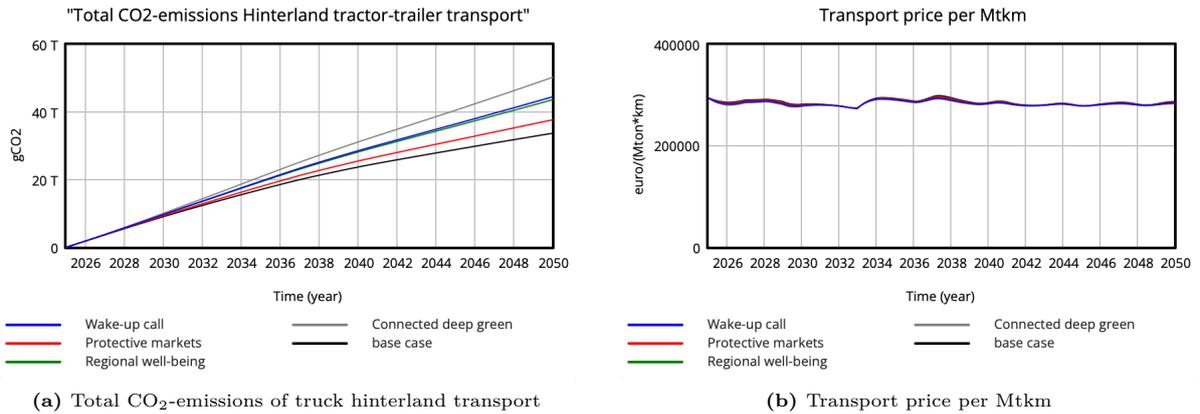


Figure 5.13: First two KPIs under different container volume scenarios

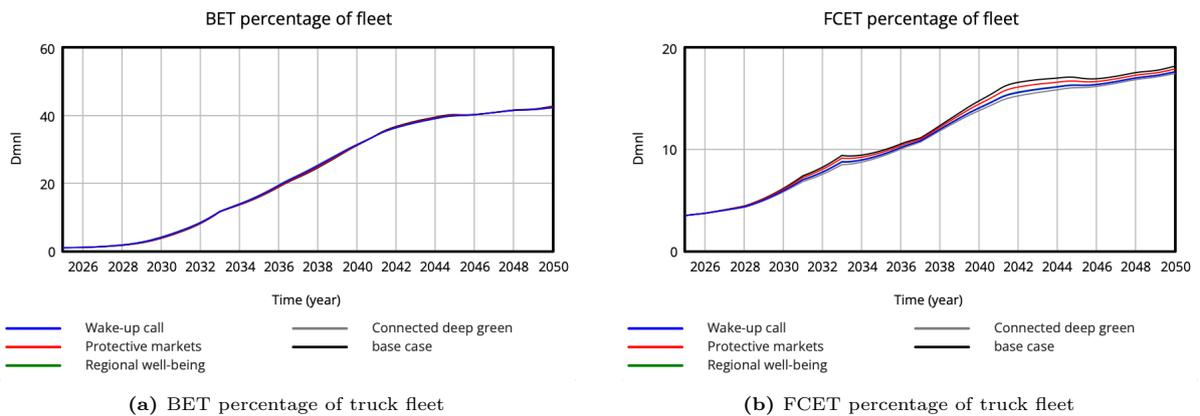


Figure 5.14: Second two KPIs under different container volume scenarios

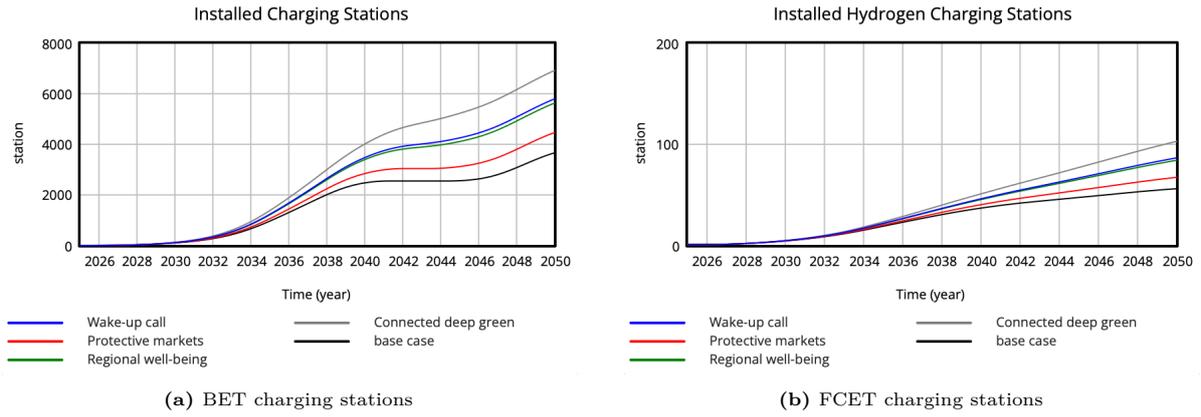


Figure 5.15: Third two KPIs under different container volume scenarios

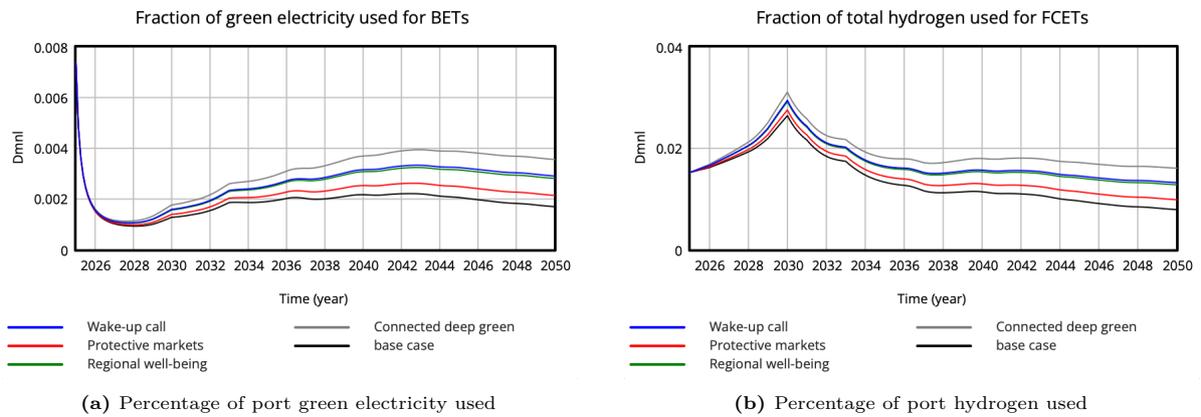


Figure 5.16: Fourth two KPIs under different container volume scenarios

The performance of KPIs in the different scenarios are compared to the base case scenario of constant container throughput volume in Figures 5.13-5.16. It can be seen clearly across the different graphs that the increase in container throughput volume leads to an equal rise in installed charging stations, fractions of energy sources used and CO₂-emissions of hinterland tractor-trailer transport. This highlights the interdependence of the subsystems. Moreover, it shows an increased pressure on the decarbonization efforts of the Port of Rotterdam, land use for charging stations and the production or import of energy sources for lower-emission truck types. However, the increase in container throughput volume does not lead to a significantly quicker adoption of lower-emission truck types relatively in comparison to the whole truck fleet, as portrayed by the overlapping lines in the graph for *BET percentage of fleet* and *FCET percentage of fleet*. By closer inspection, scenarios with a higher container throughput volume reach a slightly higher percentage for both types. This is because increased truck sales do generate more R%D funds, that can be allocated to reaching full maturity more quickly. Therefore, adoption of lower-emission trucks is slightly faster due to an increased value for maturity in the Cobb Douglas function. However, other relevant factors in the Cobb Douglas function remain the same under different scenarios. The supply side of the charging infrastructure market reacts the same to larger demand for charging stations, as long as demand growth follows the same pattern. Also, adoption rate is operationalised as a fraction of that truck type of the total truck fleet, which remains the same if the truck fleet grows across all truck types. Furthermore, the increased container throughput volume does not influence the TCO of the different truck types, which could influence the relative attractiveness of lower-emission trucks. Lastly, the balancing feedback loop Fleet dependent transport price (B5) shows its potency by mitigating the yearly increases in Mtkm under the different scenarios by initiating extra truck adoption decisions.

6

Examining performance of policy interventions

When the evaluative step is finalized and the model is operational, sensitivities can be discovered and policies shaped that steer on these sensitivities in the model. A complete and measurable picture has been created that can be used to guide discussions between the port actors that are needed to carry these costs and implement the projects. These implementations can be visualized in the SD-diagram as policy levers, that can also be tested for robustness and impact in the medium-term.

In this chapter, the following subquestion can be answered:

3. How can policy interventions by the Port of Rotterdam Authority expedite the transition towards lower-emission trucks

6.1. Relevant sensitivities influencing the KPIs

By performing a Sensitivity2All test in Vensim the parameters have been retrieved that the key performance indicators are most sensitive to. The results showed that parameters that the model behaviour is most sensitive to, are parameters that are near impossible for the Port of Rotterdam Authority to influence. *Additional yearly costs* was shown to significantly influence *CO₂-emission from Hinterland truck transport* and *Transport price per Mtkm*, but is an expense that is calculated for trucking companies outside of this model. Furthermore, *CO₂-emission from Hinterland truck transport* is most sensitive to the *Carbon intensity of diesel*, since diesel trucks make up a large part of the truck fleet during the runtime and emit the most CO₂. However, the maturity of diesel trucks is assumed to be mature in this model, with no further improvements possible. For *FCET percentage of fleet*, *Installed hydrogen charging stations* and *Fraction of total hydrogen used for FCETs* a deciding parameter value is that of *Maximum charging capacity of a hydrogen station per year*. Since this parameter value is provided by science and depends on technological improvements, it can not be altered with a policy. In order to deal with this lack of model sensitivities that can form the basis of policy interventions by the Port of Rotterdam Authority, the choice has been made to design policies not on the basis the model sensitivities. Rather, these policy interventions are aimed at capitalizing on the important feedback loops in the model. Also, the policy interventions are in line with the mandate of the Port of Rotterdam Authority, based on similar projects in the past where possible. Since the scenario analysis showed that throughput volume did not significantly influence dynamic adoption behaviour, policy interventions will not be simulated across these different scenarios.

6.2. Policy interventions

Two main aspects can be used to understand the port's relationship with the energy system: power generation, which represents the energy supply side, and energy consumption, which represents the energy demand side (Acciaro et al., 2014). Since energy supply is provided by set future predictions and can not be influenced in the model for this study, policy interventions are aimed at the demand side. Policy interventions should be aimed at making the use of lower carbon intensive energy more attractive, thereby increasing demand. Policy levers are based on the mandate of the Port of Rotterdam Authority, the central actor in the Port of Rotterdam truck hinterland transport system tasked with balancing

the KPIs that have been identified for this research. The mandate of a port authority generally consists of four roles: Landlord, regulator, operator and community manager (Acciaro et al., 2014). From these roles the port authority can initiate technological development itself or through joint ventures, set institutional interventions and facilitate actor collaborations. As landlords, port authorities can give preference to renters and logistics companies who pledge to use low-carbon transportation (Hendriks & van de Gooyert, 2023). For example, they can stipulate in concession agreements that access to charging stations or hydrogen refueling stations be provided. As regulators port authorities can penalize high-carbon diesel fleets and incentivize electric or hydrogen-powered trucks by implementing various port dues or road access fees (Hendriks & van de Gooyert, 2023). Port authorities may also set an example as operators by implementing fast-charging infrastructure, implementing low-carbon logistics solutions, and decarbonizing their own fleets of trucks (Hendriks & van de Gooyert, 2023). Lastly, port authorities are in a unique position to bring together governments, industry, and energy suppliers as community managers in order to define roadmaps for hinterland decarbonization, coordinate charging lanes, and synchronize energy infrastructure with demand (Tijan et al., 2021).

In this section three static policy interventions are identified that focus on these various roles, as well as different pressure points in the model to intervene on. These policy interventions can be qualified as static, as they do not aim to change dynamical system behaviour, but rather capitalize on the existing system behaviour and influence this in the desired direction (Auping et al., 2024). A summary of the policy interventions is provided in Table 6.1. The policies are not tested under the different container volume scenarios, as Section 5.5.3 has pointed out that these scenarios include the key performance indicators in absolute terms but do not significantly influence model behaviour.

Policy intervention	Explanation	Model variable targeted	Formalization in model
Lower-emission truck adoption rate stimulation	Policy package aimed at one-time increase of relative attractiveness of lower-emission trucks	<i>Technology adoption rate BET</i> and <i>Technology adoption rate FCET</i>	0.2 increase in adoption rate during period of 2025 to 2030
Collaborative BET-implementation project	Activating stakeholders for joint use of BETs	<i>BET adoption</i>	Increase of 1000 BETs in 2030
Port carbon-emission taxation	Taxation of CO ₂ emitted by truck hinterland transport	<i>Yearly TCO diesel truck</i> and <i>Yearly TCO FCET</i>	0.216 euro/kgCO ₂ from 2041 on

Table 6.1: Policy interventions and their formalization in the model

Lower-emission truck adoption rate stimulation

This policy intervention aims to increase adoption rate of lower-emission trucks among trucking companies. The policy intervention consists of a mix of policies, that are not further specified. The monetizable deficit of lower-emission trucks in comparison to diesel trucks can be temporarily subsidized by the Port of Rotterdam Authority. Also, feedback from the market pointed out that trucking companies are sometimes not aware of the capabilities of lower-emission trucks, such as driving range and charging costs, and the compatibility of those factors with their operational strategy [Interview 4]. Therefore, information campaigns in the form of information evenings, production and distribution of brochures and by sharing success stories can be implemented. For the adoption of BETs in Canada it is believed that information highlighting the cost-effectiveness and maturity - plus projections with their future potential - information provision is a suitable measure (Khan et al., 2021). The joint effect of the policy intervention is assumed to be an absolute adoption rate increase of 0.2. Since adoption rate in this model is defined relatively as the number of trucks in the Port of Rotterdam truck fleet driven by a technology divided by the total number of trucks in the Port of Rotterdam truck fleet, small initial lower-emission truck numbers lead to a slow start of the adoption curve of these lower-emission trucks. Since this increased adoption rate is most necessary when adoption rate is low in the early runtime, it is intended to be used from 2025 up until 2030.

Collaborative BET-implementation project

This policy intervention intends to initiate market adoption of BETs where trucking companies would not make this decision independently according to model behaviour. The policy mimics the cluster-technique that has been used for FCET-adoption of 1000 trucks between the Port of Rotterdam, the Port of Antwerp and Duisburg (Rotterdam Maritime Capital, 2022). This initiative has a large positive effect on adoption rate of FCETs in the early stages of the runtime. Therefore, the same initiative can be strived for to kick-start the adoption of BETs. From its role as community manager, the Port of Rotterdam Authority can bring together the parties required: trucking companies, truck producers, charging infrastructure operators and terminal operators. Parties are inclined to participate due to the assurance of other parties commitment, while deficits in the budget can be subsidized by the Port of Rotterdam Authority. By showing a working example of BET-transport in an important hinterland transport cluster, adoption rate is increased and other trucking companies may be tempted to follow suit. Expected is that negotiations between parties will lead to adoption of the 1000 BETs by 2030, which is when the policy intervention is implemented in the system dynamics model.

Port carbon-emission taxation

This policy intervention aims to steer adoption choice by trucking companies towards lower-emission trucks. By taxation of the CO₂ that trucks emit during all of the kilometers they drive for the Port of Rotterdam hinterland transport, it will be more attractive to adopt a lower-emission truck. The lower-emission trucks possess a lower carbon intensity, which means that less CO₂ is emitted and less tax has to be paid. This is especially true for BETs, that emit 0 gCO₂/km, and to a lesser extent for FCETs that emit 937.5 gCO₂/km because they only drive on grey hydrogen. The Port of Rotterdam Authority receives no direct payments from trucks performing hinterland transport, in which the carbon taxation could be factored in [Interview 4]. However, container terminal operators do and the Port of Rotterdam Authority has a direct relationship with them in its capacity as landlord. From an earlier process of granting a Rotterdam World Gateway (RWG) container terminal on the Maasvlakte 2 to container terminal operator DP World it was derived that sustainability factors can be included in concession contracts (de Langen et al., 2012). This leaves room for the carbon-emission taxation proposed by this technology intervention. The carbon-emission taxation clause would have to be implemented carefully, as the influence of the Port of Rotterdam Authority is limited after signing the agreement with the terminal operator (de Langen et al., 2012). Since concessions for new terminals or renegotiations of existing contracts do not occur frequently, this policy intervention can not be implemented immediately. Furthermore, the ETS2 taxation scheme taxes the same carbon-emissions and is scaled up from 2027. To not increase the financial cost for diesel truck operators all at once, it is proposed to implement this policy intervention as an extension of the ETS2 scheme. The ETS2 scheme commences in 2027 and prices are increased in 2034, after which no further price increase is proposed. Therefore, the Port carbon-emission taxation is set to double 2034 ETS2 carbon-emission prices another 7 years later, in 2041, to underline the ambition of the Port of Rotterdam to become a carbon-neutral port by 2050.

6.3. Results of implemented policy interventions

The impact of the individual policies can be found in Figure 6.1-6.4. These are discussed in more detail per policy.

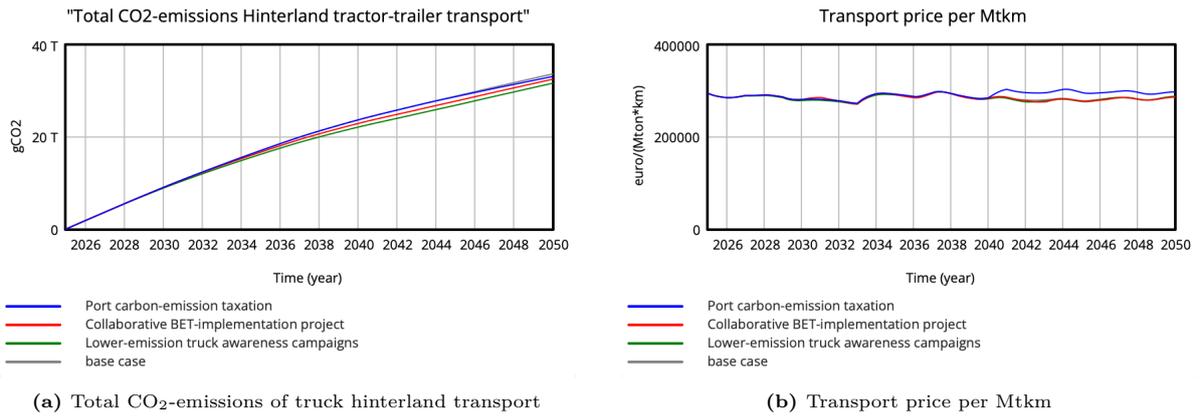


Figure 6.1: First two KPIs under different policy interventions

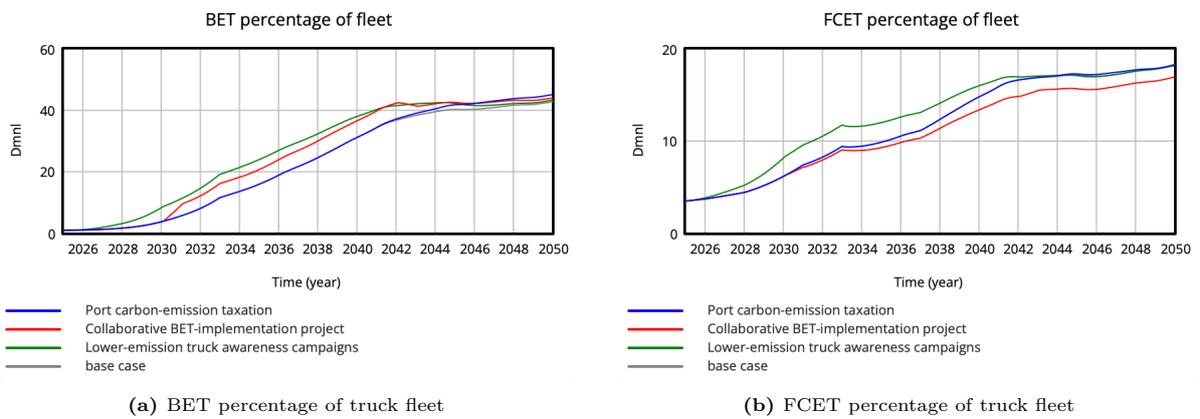


Figure 6.2: Second two KPIs under different policy interventions

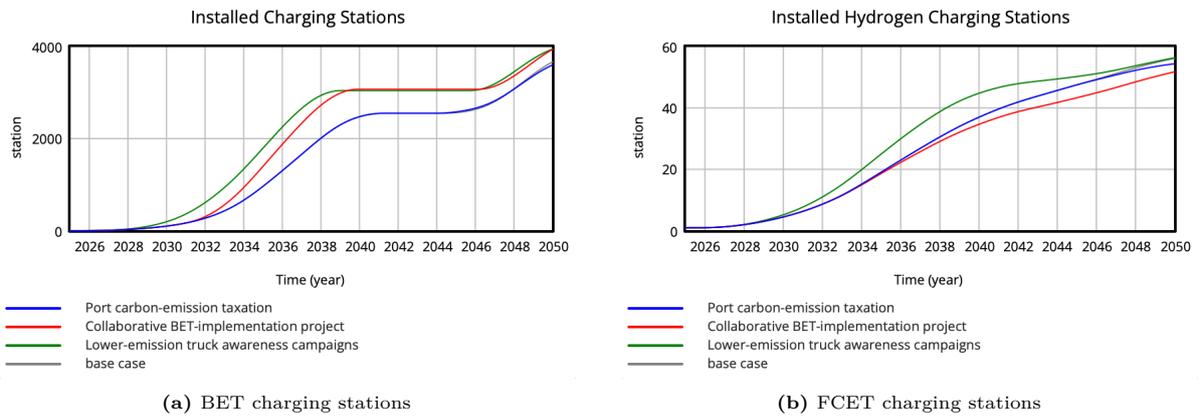


Figure 6.3: Third two KPIs under different policy interventions

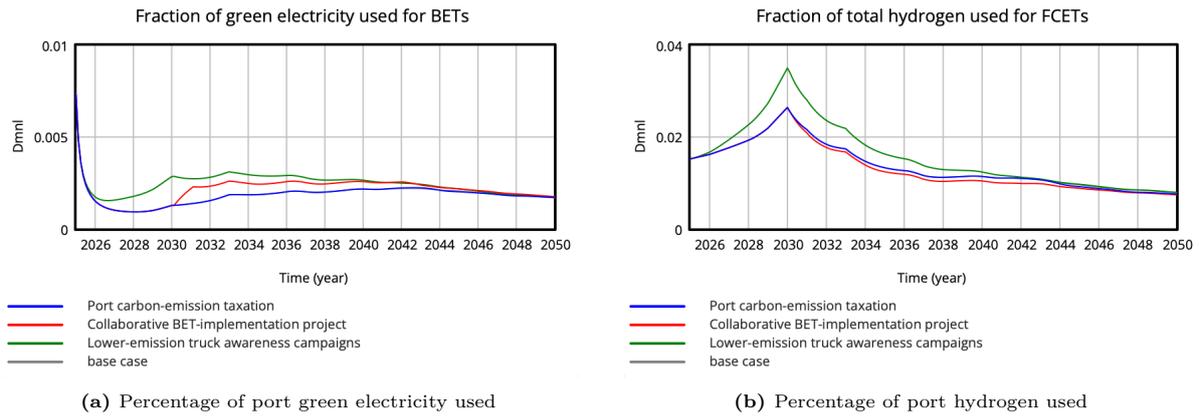


Figure 6.4: Fourth two KPIs under different policy interventions

Results for Lower-emission truck adoption rate stimulation

The adoption speed of both BETs and FCETs is significantly expedited by the lower-emissions adoption rate campaigns, as portrayed in Figure 6.2. Although the campaigns are formalized to end by 2030, the effect on adoption speed is still noticeable after this time. That is because an initial boost in adoption rate instigates feedback loop Word-of-mouth (R2), leading to exponential adoption of both types. Furthermore, as increased adoption rate leads to more lower-emission truck sales, this influx of extra R&D funds starts the feedback loop R&D cycle (R3). This reinforcing feedback loop leads to an additional exponential growth of adoption for both lower-emission truck types. The rapid adoption of both BETs and FCETs is adequately reacted to by the markets for installed charging stations, as can be seen in Figure 6.3. A worrying effect is the higher peak of *Fraction of total hydrogen used for FCETs* around 2030, shown in Figure 6.4(b). For FCETs to take up 4% of total hydrogen supply is significant, possibly surpassing its position as a relatively small user of the energy source. This is strengthened by the temporary nature of the peak, which would make it more difficult to sign a long-term contract with a hydrogen supplier, especially given the competition with industrial parties for this energy source. This policy has the highest reduction effect on *CO₂-emission from Hinterland truck transport* by almost 2 billion kg of CO₂, as is highlighted by Figure 6.1(a). This shows that an early intervention that instigates faster adoption of lower-emission trucks has large effects in the long-term.

Results for collaborative BET-implementation project

The direct effect of the implementation of the BET-trucks in 2030 is visible in Figure 6.2(a) with an increase in the *BET percentage of fleet* in comparison to the base case. This sudden increase in the number of BETs is reacted to by the market for *Installed charging stations* three years later when these years have been incorporated in the simulation for future demand for BET charging stations. This is shown in Figure 6.3(a), that also shows a more rapid growth of the number of BET charging stations from that moment on. Also, Figure 6.4(a) shows that *Fraction of green electricity used for BETs* responds with an increase to fuel the higher number of BETs part of the Port of Rotterdam truck fleet. From 2042, Figure 6.2(a) shows that the *BET percentage of fleet* reaches its peak, which is sooner than for the base case where this occurs only by 2048. Therefore, the policy has had the effect of bringing BETs to the market faster. However, the value of *BET percentage of fleet* by 2050 does not differ much from the base case, meaning that the policy effect influences adoption speed but not eventual *BET percentage of fleet*. By 2050 the BET market is mature and the required charging infrastructure is present, leaving the choice for the adoption between different truck types up to comparison of their yearly TCO. The increased adoption speed of BETs that the policy instigates is at the expense of adoption of diesel trucks and FCETs. For FCETs, Figure 6.2(b) shows that the primary effect of the policy is minimal, but does significantly hamper further adoption of FCETs, resulting in a lower *FCET percentage of fleet* by 2050. This faster adoption speed of BETs has led to a decrease of *CO₂-emission from Hinterland truck transport* by about 1.2 billion kg of CO₂, as is highlighted by Figure 6.1(a). This reduction is achieved during the runtime of the model, but will not increase further past the runtime of the model because *BET percentage of fleet* is almost similar for this policy and the base case by the end of the runtime. Also, Figure 6.1(b) shows that faster adoption of BETs has led to a slightly lower *Transport*

price per Mtkm, due to its lowest yearly TCO out of the three truck types. The price elasticity of this lower *Transport price per Mtkm* leads to a higher *Yearly Mtkm of containers for hinterland transport trucks*, an effect that is reinforced by feedback loop Transport price attractiveness (R1). Therefore, the decrease in *CO₂-emission from Hinterland truck transport* is hindered by the larger truck fleet size required to transport this increased *Yearly Mtkm of containers for hinterland transport trucks*.

Results for port carbon-emission taxation

From the moment that the port carbon-emission taxation is installed in 2041, an increase can be seen for the *BET percentage of fleet* in Figure 6.2(a). This least polluting truck type sees its yearly TCO remain the same, while FCETS and even more so diesel trucks see their yearly TCO increase. This gap widens up until the end of the runtime in 2050, which can be seen as a renewed growth cycle of BET adoption due to its increased adoption rate and the initiating effects this has on feedback loop Word-of-mouth (R2). *BET percentage of fleet* in Figure 6.2(b) remains relatively the same in comparison to the base case, meaning that BETs primarily take market share away from diesel trucks. The increased yearly TCO that the carbon-emission taxation causes for diesel trucks and FCETs are visible in Figure 6.1(b), that shows a sharp increase in *Transport price per Mtkm*. The price elasticity of this higher *Transport price per Mtkm* leads to a lower *Yearly Mtkm of containers for hinterland transport trucks*, an effect that is reinforced by feedback loop Transport price attractiveness (R1). This decreased transport demand requires a smaller truck fleet, that emits less CO₂ in absolute terms, as is also visible in Figure 6.1(a). This CO₂-reduction is strengthened by adoption being nudged more towards a choice for BETs due to the policy. However, since the runtime from the installment of the policy up until the end of the runtime is small, absolute CO₂-reduction is marginal. The policy does show the effects that a carbon-emission taxation has on the attractiveness of a BETs relatively to its competitors, and the effects it can have beyond 2050.

6.4. Comparing policy intervention effectiveness

Both collaborative BET-implementation project and Lower-emission truck adoption rate stimulation expedite the adoption of lower-emission trucks. The policy intervention of Lower-emission truck adoption rate stimulation does this more effectively, because it can be implemented immediately in 2025. In this phase lower-emission truck adoption is experiencing difficulties to get started. Once the initial growth phase has passed, reinforcing feedback loops take over and aid the adoption of lower-emission trucks. The policy intervention of lower-emission truck adoption rate gives an initial push that helps to overcome the initial growth phase, while the policy intervention of collaborative BET-implementation can only be implemented by 2030 due to the required preparatory years to launch a project containing such physical elements. The end results for *BET percentage of fleet* and *FCET percentage of fleet* are similar for both policies, although Lower-emission truck adoption rate stimulation reduce more CO₂ in the meantime due to its earlier effect on adoption speed.

Port carbon-emission taxation is implemented only by 2040 and therefore has a smaller influence on adoption speed than the other policies. However, the results have shown that this policy does instigate a second exponential growth phase for adoption of BETs, the least CO₂-emitting truck type. Since BETs also possess the lowest yearly TCO, the effect of increased TCO for the other truck types that increase *Transport price per Mtkm* are partly mitigated. This mitigating effect becomes larger as BETs take over a larger share of the Port of Rotterdam truck fleet. With the short effect period of the policy, *Yearly Mtkm of containers for hinterland transport trucks* decreases, but with the large container volume increases projected by scenarios this decrease is only marginal. With container volume throughput rising regardlessly, the Port of Rotterdam Authority can focus on green growth rather than merely growth in larger quantities.

7

Discussion and limitations

This chapter interprets the study's findings and situates them in relation to the academic field and the societal discussion surrounding the topic of truck hinterland transport decarbonisation. The discussion focuses on the model, dynamic hypotheses and results, academic relevance and societal relevance. This analysis forms the starting point for naming the relevant limitations of the model concerning model capacity, tested policies and data.

7.1. Discussion

In this section points are discussed related to four core areas: the model, dynamic hypotheses and policy results, academic relevance and societal relevance.

7.1.1. Discussion of the model

The construction of the system dynamics model was aimed at studying the adoption rate of different carbon intensity of energy reducing technologies. This was done specifically within the context of the Port of Rotterdam, an energy hub that strives to be a frontrunner when it comes to decarbonisation of transport. Also, this allowed for inclusion of specific parameter values that steer the adoption rate for a specific truck fleet. Three distinct carbon intensity of energy reducing technologies promising for the Port of Rotterdam were identified from Lechtenböhmer et al. (2018): use of e-diesel in diesel trucks, replacement of diesel trucks by BETs and replacement of diesel trucks by FCETs. From the literature research in Chapter 4 and preliminary modelling results incorporating energy source prices and ETS2 carbon-taxation, certain technologies were (partly) excluded due to their lack of price competitiveness in a container transport market that is characterized by severe price competition. E-diesel was limited to a percentual use according to RED III legislation. Also, due to reports of marginal price decrease in green hydrogen, it was assumed that FCETs drive on the cheapest energy source available with grey hydrogen. Even though the Port of Rotterdam is developing blue hydrogen projects, this technology is typically thought of as a temporary fix rather than a long-term solution. Blue hydrogen is produced using natural gas with CCS, which has the downsides of upstream methane leakage rates and residual CO₂ emissions because not all emissions can be captured. The goal of this research is to reach a carbon-neutral truck hinterland transport by 2050, which is why blue hydrogen is excluded from the study. Furthermore, blue hydrogen reactors run the risk of becoming stranded assets before 2050 due to the North Sea's limited CCS capability. Lastly, blue hydrogen is more expensive than grey hydrogen, which would drive the fuel choice of trucking companies towards grey hydrogen (Montel, 2025). Policy interventions could help close this gap, but given the transition role of blue hydrogen it was decided to not include these policy interventions in this research. Therefore, the system dynamics model focused on competing truck types, for which a fleet-centred model has been developed.

In Chapter 4 several factors were identified that are crucial to the adoption of lower-emission truck types; availability of charging infrastructure, technology maturity, technology adoption rate and availability of required energy sources. These factors and their internal dynamics were modelled as sub-models. At the same time, these sub-models showed interdependency that was possible to model with the use of system dynamics. By incorporating these sub-models in an aggregated model, a complete and measurable image of the adoption speed was created, as well as providing the opportunity for the identification of potential hindrances during this adoption process.

The adoption preference of trucking companies was based on the Cobb Douglas function. Together, the technology maturity, technology adoption rate and availability of charging infrastructure produced an indication of the attractiveness of the truck types. Factors that are all present in the mature market for diesel trucks, but not for alternatives that are just entering the market. The result of the Cobb Douglas function was combined with yearly TCO of the truck types, to include the cost-minimizing mindset of the container transport industry. The lifetime utilized in this study to calculate the annual TCO is modelled as a vehicle's whole operational duration. This presumption was deemed crucial for conveying comparison findings for a study on total cost of ownership. Other TCO studies, however, have instead taken the vehicle's lifetime into account when calculating the ownership payback period (Noll et al., 2022). Depending on the preferences of the fleet owner or investor, payback times usually vary from three to five years. The lifetime parameter, which moves the cost focus from Capital Expenditures (CAPEX) to OPEX, shows high sensitivity in the TCO results. Trucks with low kilometer-based running costs, such as BETs, are competitive because high lifetime assumptions indicate greater operational kilometers travelled. This has been mitigated by only taking into account kilometers travelled within truck hinterland transport for the Port of Rotterdam. In reality, trucking companies drive additional kilometers on a yearly basis to optimize their routing. That results in an increase the yearly number of kilometers which would make BETs, the truck type with lowest cost per kilometer, more attractive in comparison to its competitors. Additionally, a more thorough examination of comparable costs under payback period assumptions would broaden our understanding of drive-technology competition for circumstances that would be more suited to an investor's criterion for making decisions, even though this model adopts a total operational period approach.

With the use of the Cobb Douglas a relative attractiveness is calculated for the truck types in the model. The central research question in this study assesses the viability of carbon intensity of energy reducing technologies for trucks. Viability is measured by this model as relative attractiveness; when the relative attractiveness of lower-emission trucks surpasses that of diesel trucks, this lower-emission truck type is viable for segments of the trucking companies that operate in Port of Rotterdam hinterland transport. The model shows when this level of relative attractiveness is achieved and by which factors it is hampered within the timeframe before 2050. Model results have showed that BETs, the technology with the highest reduction of carbon intensity of energy, can obtain the highest level of relative attractiveness by around 2044. Although the viability of FCETs is hampered by the costliness of charging infrastructure construction, the technology does develop and obtains a relative attractiveness level. Hence, it competes with BETs and takes market share away from BETs, while FCETs have a smaller impact on the reduction of CO₂-emissions because they are expected to drive on grey hydrogen up until 2050.

7.1.2. Discussion of dynamic hypotheses and policy results

Three dynamic hypotheses were formulated in Section 5.2.6. These dynamic hypotheses were based on scientific literature that described feedback loops active in the system under analysis. These feedback loops were rebuilt in a system dynamics environment and validated with experts by performing the structure-verification test described in Appendix D.2.2. The medium-term analysis used in this research gave these feedback loops from dynamic hypotheses an adequate amount of time to develop and show their balancing or reinforcing behaviour. Policy interventions were also designed to influence these feedback loops in order to obtain the desired system behaviour.

First of all, the chicken-and-egg-problem for truck adoption and charging infrastructure has been studied for BETs and FCETs. The charging infrastructure markets for both truck types have been designed with a fraction of profit per unit of energy delivered that passes the investment threshold for investors to construct a charging station. Sufficient demand for the charging infrastructure needed to be present from trucks in the truck fleet that make use of those energy sources, but system dynamics has proven useful for showing future benefits to investors by predicting future demand that would motivate investors to start the construction of charging stations already in the present. Therefore, the markets for charging infrastructure of both truck types were able to respond to increasing market demand, although with a construction delay. With this strategy, the chicken-and-egg problem has been faced by providing the right investment climate for charging infrastructure. On the other side, this implies that trucking companies operating BETs and FCETs are dependent on the asking price for energy sources that are set on the supply side. This decides the price per kilometer and therefore also the yearly TCO, which

influences the relative attractiveness of this truck type in the new truck adoption decision.

By focusing the model on an attractive investment climate on the supply side, the demand side consisting of BETs and FCETs in use formed an interesting lever for policy interventions. The adoption curve of BETs and FCETs was found to be s-shaped, which means that specifically in the early years where the adoption curve is near flat policies can make a difference. Two policies, Lower-emission truck adoption rate stimulation and collaborative BET-implementation project, showed that these interventions should be implemented as early as possible to break the deadlock, thereby confirming the dynamic hypothesis.

Secondly, the dynamic hypothesis predicting exponential lower-emission truck adoption can be validated in part. This exponential growth is only true during the middle part of the s-shaped adoption curve that has been found to be applicable. Even after the direct effects of the policies Lower-emission truck adoption rate stimulation and collaborative BET-implementation project stop, an ongoing effect can be witnessed on adoption. Due to the reinforcing feedback loops Word-of-mouth (R2) and R&D Cycle (R3), the slope of adoption speed becomes steeper and full maturity for lower-emission trucks is obtained earlier. During this exponential growth phase, the infrastructure investors have difficulty keeping up with demand, while overshooting supply towards the end of the exponential growth phase. Especially for hydrogen charging stations, that due to the high OPEX have a worse investment climate than BET charging stations, the supply of enough hydrogen charging stations forms a barrier to more rapid adaptation of FCETs. However, in the early stages, low values of maturity and adoption rate are inputted in the feedback loops, resulting in a deadlock and slow startup phase. Before becoming fully mature, increasing the adoption rate loses its exponential character due to the increased R&D revenue that is required to realize further technology improvements.

Lastly, it was hypothesized that lower-emission trucks would lead to lower transport costs. This was found to be true, already from the beginning of the runtime. Due to a decrease in battery prizes for BETs and FCETs, as well as increased carbon-taxes under the ETS2 scheme, this price gap in yearly TCO with diesel trucks only became larger. An important note to make in the light of this finding is that depot charging was utilized for BETs as a cheaper alternative to fast-charging, that is characterized by significantly higher prices per kWh in The Netherlands. Also, FCETs in this model only drive on grey hydrogen, that is cheaper than green hydrogen. Comparison of yearly TCO for the different truck types shows that these do not differ greatly, which shows that lower-emission trucks can be price competitive. The eventual effect of the adoption of these lower-emission trucks on the *Transport price per Mtkm* could be witnessed in the model behaviour, but only marginally since the truck adoption decision in the model is based on relative attractiveness. Therefore, a significant and sudden switch to a lower-emission truck type for a large percentage of the truck fleet is not expected. This effect is strengthened by the fact that the ageing chain in the model only allows for new adoption choices when a truck is exported or scrapped, or when hinterland truck transport increases in container volume.

7.1.3. Discussion of academic relevance

Other research publications have recognized the potential of ports as energy hubs and utilized system dynamics to study decarbonization in ports (Ghisolfi et al., 2024; Hou & Geerlings, 2016; Xu et al., 2021; Zhong et al., 2023). In comparison to those, the scope for this research has been narrowed by looking only at carbon intensity of energy reducing technologies for truck transport, and policies that can expedite the use of these. By narrowing the scope, the trade-offs between different subtypes of carbon intensity of energy reducing technologies become apparent. Moreover, more depth could be achieved in the study of a more limited number of technologies. Therefore, system behaviour could be retraced more accurately and policy interventions could be targeted at more specific dynamic behaviour.

The most value of this study lies in the combination of different factors relevant to the adoption of lower-emission trucks. By narrowing the scope for the model to lower-emission trucks the market for charging infrastructure could be included in detail for both BETs and FCETs. By including infrastructural aspects of transition, that are absent in higher-level system dynamics research (Zhong et al., 2023), construction time and delay in market supply could be modelled. That way, it was possible to recognize when the availability of charging infrastructure formed a barrier to lower-emission truck adoption, which proved to be the case mostly for hydrogen charging stations. By using the charging station availability as direct input for the truck adoption decision with the Cobb Douglas function, interesting new dynamic

behaviour became apparent. The results of this study align with those of other research by appointing BETs as the most viable carbon content of energy reducing technology for trucks in Port of Rotterdam hinterland transport for the future (TNO, 2021). However, by adding the infrastructural development in the model, this study provides additional insights into when this adoption can occur. This provides the additional benefit of knowing when policy interventions should be timed. Also, the effects of truck adoption were directly linked to a sub-model of truck hinterland transport, that used the *Annual total yearly TCO* due to lower-emission truck adoption to calculate *Transport price per Mtkm*, which was connected to yearly container volume through a price elasticity. By showing the effect of lower-emission truck adoption not just on decarbonization, but also on the trade position of the port as a whole, a necessary additional perspective was added. Since it is Port Authorities that task themselves with decarbonization of hinterland transport, it is relevant to include the effect it has on the position of the port that the Port Authority is also responsible for.

The interaction between sub-systems in the model was validated through interviews with experts, meaning that academic theories were validated in a new context by different experts, both from academia and the transport industry. By utilizing a semi-structured interview style the interviewees had the opportunity to table input from their own work. The experts often focused on only one of the carbon intensity of energy reducing technologies. By discussing it in the broader context in relation to competing technologies in this research, the interviews have had the additional effect of having the interviewees reflect on their own research. Not only as to how it fits into broader research, but also how it connects to the concrete example of port hinterland transport for the Port of Rotterdam. This has led to engaging conversations, that have hopefully led to new perspectives and ideas in the academic world.

In this study, no sensitive variables could be targeted with policy interventions with the means of the Port of Rotterdam Authority. Therefore, technology-neutral policy interventions were designed, aimed at dynamic processes in the model. However, technology-neutral policy mixes may not encourage the rapid adoption of low-carbon technologies required to achieve emission reduction targets, according to prior studies (Azar & Sandén, 2011; Carton, 2016; Skjærseth et al., 2023; Tongur & Engwall, 2017). Investors and prospective innovation adopters may become more contested and uncertain about future technical pathways as a result of authorities' refusal to support particular low-carbon advances, which could lengthen transition timelines (Geels, 2012; Geels et al., 2016; Haščić et al., 2009; Meadowcroft, 2009). Given the diversity of these technologies, other criticisms also highlight how inadequate technology-neutral approaches are at tackling the intricacies and context-specific obstacles to low-carbon transitions (Stirling, 2008). Such neutrality might occasionally even obstruct the advancement of promising innovations by ignoring important factors like economies of scale, network effects, and disparities in technological maturity. Therefore, technology-specific policies can be encouraged (Azar & Sandén, 2011; Skjærseth et al., 2023).

7.1.4. Discussion of societal relevance

Currently, the rate of adoption of carbon intensity of energy reducing technologies is very low. Chicken-and-egg problems and other uncertainties hamper investors from doing the large upfront investments required to initiate the adoption, creating a deadlock. This deadlock can not persist for too long. Targets for carbon neutrality agreed on by some industrial clusters like the Port of Rotterdam are due for 2050, while truck hinterland transport is far from obtaining that goal at the moment. Also, adoption requires time due to infrequent truck adoption decisions, charging infrastructure construction processes and market growth of lower-emission trucks. System dynamics has been used in this research to provide an option to model interventions and their future benefits to actors involved to break this deadlock and initiate action by showing pathways to sustainable success.

The study is tailored specifically to the Port of Rotterdam, which means that this energy hub gains the most insights from this research. By applying scenarios that contain simulations for their future port throughput, the role of lower-emission truck adoption can be regarded within this aggregated future. However, the model can be adapted to match truck hinterland transport of another port. Preferably in the EU, where the ETS2 carbon-taxation also contributes to system states and other parameter values are in similar ranges. These different ports can also use this study to decide the right technology to target in their concrete case, as the study specifically compares competing carbon intensity of energy

reducing technologies. For a specific port that would entail combining factors that differ per port such as the specific energy source availability, energy source prices and hinterland transport drive distances in the model to select the carbon intensity of energy reducing technology that works best for that specific port. This can also direct research and development towards the technology that is most promising, which in the model would lead to an increase in maturity that expedites adoption of lower-emission truck types. When the use of this model can aid specific European ports in designing their truck adoption strategy, network effects also arise. With many trucking companies partially operating in other European member states, as well as 10% of Port of Rotterdam hinterland transport having a foreign destination/origin, creating an EU-wide charging infrastructure network can aid the transition towards lower-emission trucks.

7.2. Limitations

This section covers limitations associated with different elements of this thesis related to three core areas: Model limitations, policy limitations and data limitations.

7.2.1. Limitations of the model

First of all, the study has used depot charging as the charging method for BETs. This charging strategy aligns with the transport node connectivity and energy hub function of the Port of Rotterdam. Furthermore, depot charging has been opted for due to its lower infrastructural investments and electricity costs (Al-Hanahi et al., 2021). The longer charging time required for depot charging in comparison to fast-charging was assumed to overlap with mandatory primary stop events after every 9 hours of driving (European Parliament and Council of the European Union, 2006), as well as with 18.21% of secondary stops that take more than 8 hours for trucks (Dimatulac et al., 2023).

However, depot charging is difficult to implement in reality. This study utilizes a fleet-centred model where the fleet is considered to be uniform instead of in the hands of individual trucking companies, where trucks perform drives only with cargo to/from the Port of Rotterdam. However, in reality the trucks are in the hands of separate trucking companies, characterized by own routing strategies and areas of operation. This leads to different optimal depot locations per trucking company instead of one central depot in the Port of Rotterdam, as has been researched for the German market BETs (Speth & Plötz, 2024). The depot charging stations constructed in the model can of course be realized in different locations rather than specifically in the Port of Rotterdam, allowing those truck companies with a truck storage location close to the Port of Rotterdam to place their depot charging station at their own location, under the same market conditions that have been modelled. However, this relocation of the depot charging station can lead to increased drive times to the Port of Rotterdam to pick up cargo, as well as local problems with net congestion. Also, it has not been considered whether depot charging will take place during periods of peak green electricity supply, which could lead to residual grid CO₂-emissions caused by grid balancing by fossil-fuel producing actors.

With this choice for depot charging, no fast-charging has been implemented in the system. Nevertheless, The Netherlands already has a near full-coverage network of public fast-charging stations that can be utilized in times of need [Interview 4]. Trucks can divert to these fast-charging stations in situations where depot charging at the central location does not align with their routing. However, electricity prices almost tenfold of real electricity prices are currently being charged at these fast-charging stations, largely due to high capital cost and high operational cost (Rabobank, 2025). When these fast-charging stations are placed in the Port of Rotterdam, similar prices are expected due to price competition with other industries for the expensive land in the port area [Interview 4]. From its position as landlord, the Port of Rotterdam Authority could attribute land specifically to charging infrastructure for trucks, but this could mean incurring a reduced rent (Acciaro et al., 2014). What the perfect position for the charging stations, depot or fast-charging, would be is something that has not been addressed in this research.

Secondly, the selection of three most promising technologies has resulted in a more in-depth comparison of their adoption and trade-offs in the medium-term. This medium-term does carry a large degree of uncertainty. How the selected technologies will develop is based on expert predictions, estimations that can not foresee unexpected events and developments. During one validation interview it was tabled that other technologies could arise as most promising in the medium-term of analysis [Interview 6]. Hydrogen

dual fuel trucks were mentioned in an earlier interview, bearing the promise of merely adjusting existing diesel trucks and less ties to availability of hydrogen charging stations [Interview 2]. This research has opted to include the most mature carbon intensity of energy reducing technologies in the case of the Port of Rotterdam. These technologies are already implementable right away in order to initiate the decarbonization of hinterland truck transport, that is expected to take time. Furthermore, these technologies are described in more detail in literature, which allowed for a more precise formalization in the model. The model does allow for extensions with other technologies, when these become more prevalent in the future or when they match the application to a different energy hub better.

Lastly, improvements to lower-emission trucks were almost exclusively aggregated in one value for maturity, that measures reliability and performance of a technology (Nieuwenhuijsen et al., 2018). Reliability and performance of a technology can increase with technological or operational advancements, such as automation in the production process. These advancements increase the attractiveness of the truck type, but can also lead to cost reductions that influence the attractiveness of the truck type by means of a lower yearly TCO. This cost reduction can occur through economies of scale or technology improvement. The only cost reduction concretely implemented in the model separately from maturity is that of reducing battery production costs. This reduces the price of BETs and FCETs over time, although the cost reduction is larger for BETs that carry a larger battery on board. Other cost-reducing technology improvements of BETs could also have been considered; more automation in the production process and an extended battery lifetime. Furthermore, the only type of BET that was deliverable in The Netherlands the past few years was a BET by Volvo [Interview 4], meaning that increased competition between BET-producers could further reduce prices in the future competition.

7.2.2. Limitations of the policies

An important limitation of the study is that it focused on enabling a faster adoption of lower-emission trucks, but this only resulted in a relative attractiveness increase of lower-emission trucks. For BETs the modelling results and implemented policies resulted in the highest percentage of truck fleet, surpassing diesel trucks. However, due to this attractiveness being relative this does not lead to a sudden shift towards BETs that would significantly flatten the curve of total CO₂-emissions of truck hinterland transport for the Port of Rotterdam. Of course, the different truck types will co-exist in the medium-term that has been used, for example to cover the 10% of foreign hinterland transports that could exceed the driving range of BETs.

This slow transition makes sense based on obstacles that have not been explicitly modelled. First of all, a governance element has been omitted; parties that steer the adoption of lower-emission trucks by providing the required energy sources and charging infrastructure are large producers of fossil energy. The currently advanced charging infrastructure for diesel trucks has been achieved by large investments by fossil energy producers that largely rely on these revenue streams, so altering this infrastructure for the technological interventions can be seen as incurring sunk costs. Therefore, the current level of infrastructure and the rigidity that it possesses can also be seen as a limiting factor for the interventions aimed at reducing CO₂-emissions (Damman & Steen, 2021). Secondly, other organizational obstacles remain for lower-emission truck adoption besides electricity prices and availability of charging infrastructure. Businesses that switch to BETs or FCETs must provide their employees with training on how to operate and maintain them, as well as additional safety procedures. The monitoring, maintenance, and charging schedules of these lower-emission truck fleets must also be incorporated into updated fleet management systems. Even though it is challenging to evaluate and incorporate these costs into the yearly TCO calculation for this study, businesses thinking about making the switch continue to pay attention to them (Rabobank, 2025).

Although these obstacles make a case for the use of relative attractiveness for the truck adoption decision, due to its use a large percentage of diesel trucks remains in the fleet, making it impossible to reach carbon-neutrality of truck hinterland transport of the Port of Rotterdam by 2050 with policy interventions by the Port of Rotterdam. This slow decarbonization effect is strengthened by the use of the Cobb Douglas function, that assumed diesel trucks to have a maximal score throughout the runtime. The modelling results showed that both BETs and FCETs can render lower yearly TCO than diesel trucks and that the market for charging infrastructure can adequately respond to increased demand.

This could provide an opening for a more discrete switch to lower-emission truck types when this is desired in order to reach the decarbonization goal for 2050. However, the systemic behaviour modelled only focuses on the transition phase and shows by when lower-emission trucks have reached their final relative attractiveness. The policies of Lower-emission truck adoption rate stimulation and collaborative BET-implementation project have shown to bring this moment of final relative attractiveness closer in the future. This moment of lower-emission truck market maturity can be used for more rigorous policies focusing on higher market adoption of BETs, the truck type with the highest relative attractiveness.

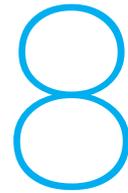
Lastly, no national policy schemes have been included that could have expedited the adoption of carbon intensity of energy reducing technologies further. Subsidy schemes such as AanZET, through which the Netherlands Enterprise Agency subsidizes a percentage of the price of a BET, have not been included (Rijksdienst voor Ondernemend Nederland, 2025). The intention was to describe the market mechanisms present in the system in their naked form, apart from relevant European regulations such as the ETS2 and RED III regulations. That way, sensitivities from the system behaviour could be used as input for the formulation of the most effective new policy interventions. Furthermore, subsidies have a temporary nature so it is unsure until which moment of the runtime the policies could have aided in increasing attractiveness of carbon intensity of energy reducing technologies in the model.

7.2.3. Limitations of the data

Due to time constraints of the study, not a great number of interviews could be performed. This could have led to bias in the responses incorporated into the study, based on the personal beliefs of respondents. This was mitigated by selecting a diverse group of respondents, from different fields and therefore with different aims for the research result. Furthermore, claims from interviews were compared with scientific literature where possible. Nonetheless, key assumptions in the model have been based on interviews or own estimations. This limitation underlines that the study's results should be considered illustrative rather than predictive.

It would have been interesting to engage more with trucking companies, as data about their decision-making shapes the adoption of lower-emission trucks. As explained earlier in the discussion, the choice for the locations of new charging stations for BETs and FCETs depends on the routing data of trucking companies. In this research, trucks were assumed to be part of one uniform Port of Rotterdam truck fleet that performed transports only for the Port of Rotterdam hinterland transport. Since the average distance was available for truck hinterland transports, the range of different truck types could be matched with charging schedules at the central transport node of the Port of Rotterdam.

The addition of a dataset containing information about transports outside of hinterland transport could aid in designing more specified charging infrastructure strategies, that align better with the needs of trucking companies. This data would have to be retrieved from individual trucking companies. It would be beneficial to divide this dataset into different segments of trucking company types. By doing so, not only generalized attractiveness from this study can be applied but also a specific type of lower-emission truck can be proposed based on the specific needs of that segment.



Conclusion and Recommendations

This chapter answers the central research question by drawing on the key findings from the preceding chapters. It also outlines recommendations for decarbonization of Port of Rotterdam truck hinterland transport. The chapter concludes by discussing the possible directions for future research.

8.1. Answer to the main research question

This thesis aimed to comprehend the dynamics underlying adoption of lower carbon intensity of energy technologies and assess whether policies could expedite this issue within the context of the Port of Rotterdam truck hinterland transport. Specifically, it addressed the main research question:

What is the most viable technology for the reduction of the carbon intensity of energy for trucks involved in the dynamic hinterland transport of the port of Rotterdam?

From the range of existing carbon content of energy intensity reducing technologies BETs, FCETs and e-diesel were found to be the most well-established technologies, which makes these technologies more easily deployable before 2050. Based on a comparative analysis, BETs are the most practical technique to lower carbon intensity. They have the advantages of being more technologically advanced, compatible with the Port of Rotterdam goals for renewable wind electricity, and appropriate for the primarily short-distance hinterland journeys that depot charging can accommodate. E-diesel is easy to implement in diesel trucks but is unlikely to become cost-competitive with diesel and will therefore remain limited to regulatory quotas. Long-distance and international routes could be served by FCETs, but responsiveness of charging infrastructure construction, low initial maturity, higher yearly TCO and use of grey hydrogen prevent widespread adoption before 2050. Additional evidence from system dynamics modeling shows that adoption is dependent on reinforcing cycles of maturity and adoption rate, with "chicken-and-egg" dynamics limiting initial uptake. By removing early obstacles and cutting the time to maturity by a number of years, the Port of Rotterdam Authority's policy interventions can expedite adoption. BETs are the most viable technology to lower carbon intensity of energy for truck hinterland transport of the Port of Rotterdam, with its relative attractiveness already surpassing that of diesel trucks around 2044. However, more steps outside the port's mandate will be required to turn relative attractiveness of this truck type into full adoption in order to reach carbon neutrality by 2050.

Finally, it's critical to understand that the model's predictive power is limited by the issues covered in the discussion and limitations in Chapter 7. The model should not be viewed as a prediction tool, even though it is a useful conceptual and exploratory tool that could serve as a springboard for more complex modeling frameworks.

8.2. Answers to the sub-questions

The results from the three sub-questions are summarized in this section, which also offers a structured knowledge overview of how adoption of energy technologies with lower carbon intensity happens and can be accelerated. While the last two sub-questions demonstrate how formal modelling explains observable behaviours and assesses alternative tactics, the first sub-question investigates the most feasible technologies in this local environment based on a number of parameters.

(1) Which technologies for reduction of carbon intensity of energy for trucks align with the position of the port of Rotterdam as energy hub?

Chapter 4 provided more in-depth insights into three specific carbon intensity of energy reducing technologies already identified for the Port of Rotterdam truck hinterland transport: BETs, FCETs and e-diesel. From literature research a framework of five factors vital for adoption was constructed: available charging infrastructure, technology maturity, technology adoption rate, energy source availability and lifecycle costs and energy efficiency. Semi-structured expert interviews aided in identifying relevant barriers for adoption across these five different factors. E-diesel is attractive due to its conformity with modern diesel trucks in the Port of Rotterdam and easy implementability of charging infrastructure, but since e-diesel is not expected to be price-competitive with diesel will be utilized only according to legislative quotas. FCETs can be particularly useful for the 10% of truck hinterland transport with a foreign origin/destination, but the technology is immature and this causes uncertainty about fluctuating hydrogen prices, truck prices and availability of charging infrastructure. BETs are the most mature technology out of the three, with the largest carbon emission reduction potential fueled by the ambitious green wind electricity generation plans from the Port of Rotterdam. The short driving range of BETs is masked by the large fraction of short-distance Port of Rotterdam hinterland trips, that can be covered with depot charging at the central transport node of the Port of Rotterdam. Each technology scores differently across the five adoption factors, with adoption only likely to occur when all five are present. Trade-offs do not provide information about their quantitative impact, interaction and future development. Therefore, it was opted to study these factors in an aggregated system dynamics model.

(2) How can the relevant dynamic factors for transition to lower carbon intensive energy for truck hinterland transport of the port of Rotterdam be formalised in a System Dynamics model?

Chapter 5 followed the Delft method for system dynamics to construct a scientifically novel system in Vensim that models the interdependency between the five factors vital for the adoption of carbon intensity of energy reducing technologies. These different factors formed the basis for the different sub-models besides being linked with the effect on total truck hinterland transport in the Port of Rotterdam, with key performance indicators being appointed to measure the performance of these individual sub-models as a result of aggregated model systemic behaviour. This aggregated dynamic system behaviour was characterized by six feedback loops, that cause chicken-and-egg problematic early-on, exponential adoption growth thereafter and balancing transport price behaviour due to price elasticity. Delays were found to not significantly hamper charging infrastructure supply, while the speed of adoption of lower-emission trucks is dependent on lifetime of a truck in the truck fleet before a new adoption decision is taken.

(3) How can policy interventions by the Port of Rotterdam Authority aid in expediting the transition towards lower-emission trucks before 2050?

Chapter 6 has implemented three policies that the Port of Rotterdam Authority can take to leverage the systemic behaviour of the formalized model. The policy of port carbon-emission taxation has shown what level of relative attractiveness lower-emission trucks can obtain at the end of their adoption around 2044. Lower-emission truck adoption rate stimulation expedited the adoption of BETs and FCETs the most, by leveraging the adoption rate feedback loop. Since this policy intervention is directly implementable, chicken-and-egg problems leading to a slow initial growth phase are defied. The policy intervention renders more long-term effects and quicker adoption than the collaborative BET-implementation project, which was aimed at leveraging the maturity feedback loop. These policies are aimed at bringing forward the point of market maturity of lower-emission trucks, so that with that level of relative attractiveness a larger shift in technology can be realized. Also, full maturity of lower-emission trucks can be reached within a shorter timespan, allowing for timely policies that push the further adoption of these lower-emission trucks before 2050. The maximum shortening of this timeframe is about three years, meaning the system is relatively policy-resistant. Therefore, further policies beyond

the means of the Port of Rotterdam, are required to achieve carbon neutrality of the truck hinterland transport by 2050. The model has shown that the relative attractiveness of BETs can surpass that of diesel trucks, but is not able to display a more radical shift towards BETs. That would require more elaborate discourse with trucking companies concerning their routing data and operational strategy outside of the Port of Rotterdam hinterland transport and their alignment with depot charging.

8.3. Recommendations

Based on the conclusions, discussion and limitations of this study, three recommendations are presented for the Port of Rotterdam Authority for obtaining decarbonization of truck hinterland transport.

Prioritize early-stage policy interventions

The modelling results have demonstrated that early policy interventions mitigate the chicken-and-egg problematic related to truck adoption and the construction of the necessary charging infrastructure, as well as initiating adoption rate and maturity feedback loops that lead to exponential growth of adoption. The positive effect of early-stage is increasingly noticeable as time passes, even when the implementation of the policy has stopped. Timely action is also required to complete adoption before 2050, since adoption is slowed down by long-term truck investments and charging infrastructure construction periods.

Integrate into broader national approach

The policies tested in this study fell within the mandate and the means of the Port of Rotterdam Authority. Due to the limited scope this offers for policies, no significant reductions in carbon-emissions could be achieved with the policies tested. The model developed in this research can be extended by implementing current national policy schemes. Also, it could be used to communicate to national government bodies - with larger mandates and budgets - what is necessary to make the Port of Rotterdam a beach head for decarbonization of truck transport.

Focus on policies targeting BETs

While model results have shown that relative attractiveness for BETs surpasses that of diesel trucks, relative attractiveness of FCETs stays behind. This difference for the lower-emission trucks is explained by multiple factors on which BETs perform better: yearly TCO, responsive supply of charging infrastructure, CO₂-emission reduction and higher initial maturity. Therefore, to increase the effect of policy interventions on the transition of the truck fleet to lower-emission models, BETs as the most promising lower-emission truck type should be prioritized. Since 90% of hinterland truck transports is within the borders of The Netherlands, the driving range of BETs forms no obstacle. For that 10% of foreign transports, various options exist to decarbonize this final section of truck hinterland transport. First, the use of BETs while ensuring that fast-charging is available along the route. Secondly, continued use of diesel trucks or adoption of FCETs for which CO₂-emissions can be compensated by other sectors in the Port of Rotterdam ecosystem.

8.4. Directions for future research

The conclusions of this research bear the asking of new research questions, while limitations of this research have shown where additional research is required. Future research could expand on this study in various areas, described in the following subsections.

8.4.1. Multi-case research design

First, by using a multi-case research design, researchers can increase the findings' generalizability. Although this study provides detailed information on truck hinterland transit for the Port of Rotterdam's particular energy hub, its findings are still context-specific and could not be applicable to other industries or geographical areas. Researchers can investigate if adoption patterns vary in other situations by performing comparative case studies across other industries. By examining several cases, it would be possible to identify patterns in various situations and uncover the circumstances that lead to the success or failure of particular interaction tactics. This method would refine the theoretical model and define its parameters, shifting the study from illustrative to analytically generalizable.

8.4.2. Linking truck type attractiveness to specific trucking companies

Attractiveness of lower-emission truck types in this study was calculated for the aggregated truck fleet of Port of Rotterdam hinterland transport. This approach ignored differences among trucking companies. These differences in operational strategy, routing and geographic area serviced decide the placement location of charging stations and the attractiveness of a truck type specifically for that trucking company. Therefore, engaging more with the trucking sector in order to build a dataset containing this information could lead to better insights regarding the right policies to target these different segments of trucking companies.

8.4.3. Incorporating vehicle diversity for improved transport modelling

Currently, the model functions at a high level of aggregation, treating vehicles of a particular type as a homogeneous group without making any distinctions about age-related energy efficiency or size. This simplification makes it more difficult to identify variations that have a major impact on fuel consumption and yearly transportation activities. To increase the accuracy of the model, future studies could concentrate on adding more thorough vehicle classifications. The model's ageing chain already provides a starting point for this. Such enhancements would boost the accuracy of long-term energy and transportation forecasts and enable a more comprehensive study.

8.4.4. Replacing depot charging by fast-charging

This study opted for depot charging as the preferred charging method, due to its lower electricity price and overlap with primary and secondary stop events for trucks. However, this choice has not been validated with trucking companies. In case they deem fast-charging more in line with their operational strategy and are willing to pay the surplus for this, a version of the model should be made that includes fast-charging. The sub-model *Charging infrastructure BET* can be adjusted simply by changing the values for *Construction cost electric charging station* and *Maximum charging capacity of a station per year*. Either fast-charging can fully replace depot charging in this future study, or both charging methods can co-exist, allowing for an approach tailored better to differing charging needs from different trucking companies.

8.4.5. Data reporting for energy transition

Due to the fast-changing nature of the energy sector, it proved difficult to find accurate and up-to-date sources to use as input for the system dynamics model. For example, projections for the FCET-market have become more gloomy over recent years, but (scientific) literature is still overcrowded with older and much more positive reports on the future of FCETs. Therefore, keeping this information up-to-date is vital for adequate data-based policymaking and should be prioritized. Yearly or regularly released reports from renowned institutions can aid in providing authoritative knowledge, thereby avoiding hype or the spread of misinformation.

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Literature review strategy

This Appendix describes the compartmentalized literature review that was performed in rounds to retrieve the state of the art of scientific literature that forms the background for this research.

A.1. Increasing importance of truck hinterland transport in the Port of Rotterdam

For round 1 the goal was to find reports that can show insight into what levels of shipping can be expected in the future, specifically in the port of Rotterdam or The Netherlands. Levels of shipping are a key factor because these influence the use of the truck modality. Although the port of Rotterdam forms a gateway port for Northwestern Europe, it was chosen to not include Northwestern Europe to get more specific reports.

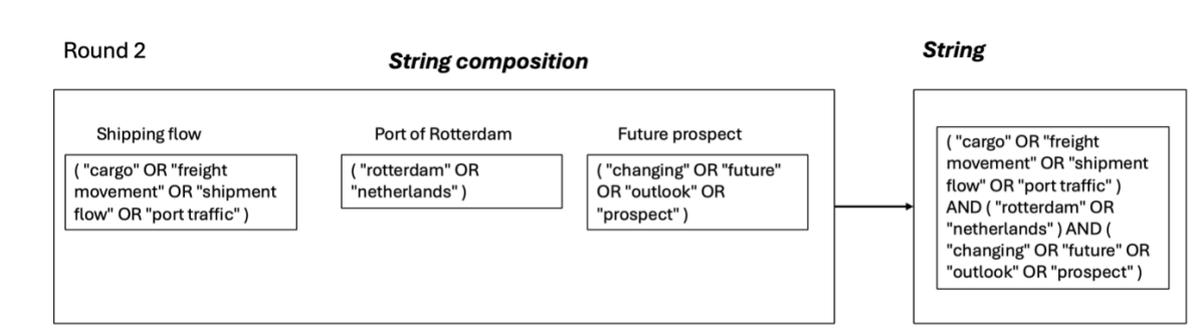


Figure A.1: Literature research round 1

In total 29 reports were found. These reports can contain numbers that can be used to base the System Dynamics model on, which is specifically designed for the ecosystem of the port of Rotterdam. Therefore, it is vital for the reliability of the model to include local shipping predictions.

A.2. Technological advancements towards a future of less carbon intensive truck transport

This second round specifically started by looking in Scopus at which alternative technologies exist for combustion engine trucks, that can accommodate the hinterland transport with a lower carbon intensity of energy used. The aim was to look at the most recent developments in this rapidly changing sector, which is guaranteed by taking 2020 as the starting year for included publications.

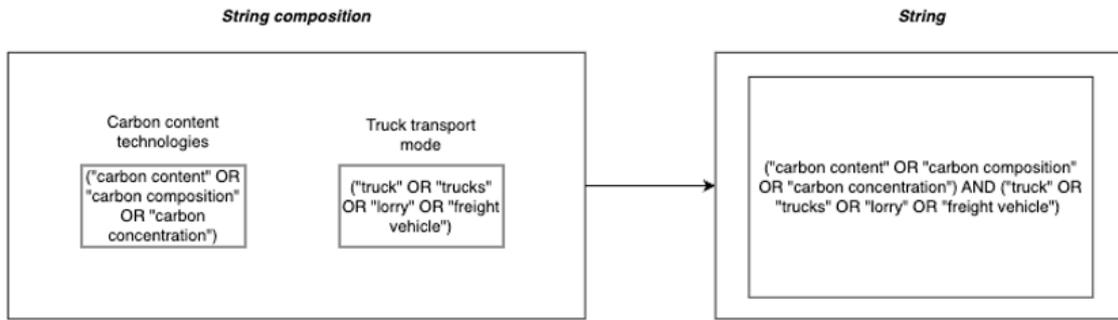


Figure A.2: Literature research round 2

This search has yielded 20 results. From these sources a shortlist of promising and feasible technologies will be distilled. From interviews with stakeholders from the Port of Rotterdam, a preliminary judgment based on professional expertise will remove technologies from the shortlist that are believed to not work in the PoR ecosystem. The remaining technologies will be explored further. These technologies will also be implemented and tested in the System Dynamics model to assess their impact.

A.3. Decarbonization of truck transport specifically at energy hubs

The third round wishes to gain insight into whether industrial clusters that serves as energy hubs have been researching pathways for decarbonizing truck transport. The initial idea for this search round was to find literature that relates truck transport to the presence of energy hubs that can aid in the decarbonization of this truck transport. Combining trucks and energy hub has resulted in 11 sources since 2015.

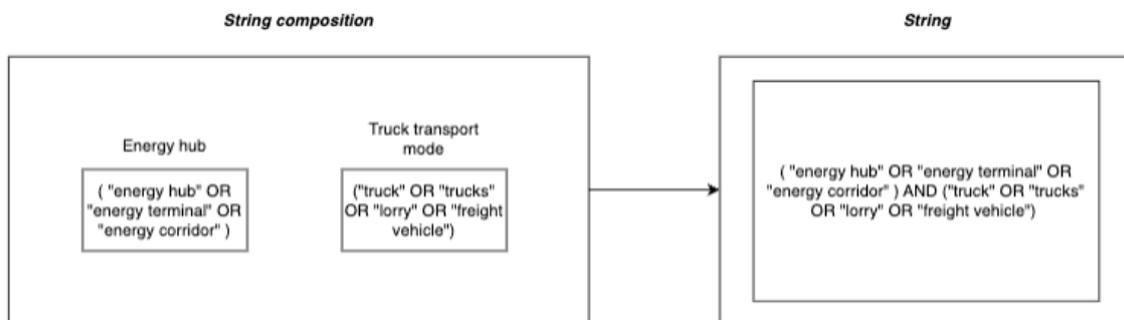


Figure A.3: Literature research round 3

There is some additional research commencing in some of the frontrunner ports to decarbonize the hinterland transport, but this research is not linked yet directly to the large energy supply that the port has as its advantage. The knowledge of what needs to be present in terms of technology infrastructure in order to make the transition will have to come from the search in round 2, which is not specifically related to ports.

A.4. System dynamics as an analytical tool for exploring long-term uncertainty of sustainable truck implementation

The goal for round 4 was to find research that has used system dynamics to improve hinterland transport of ports.

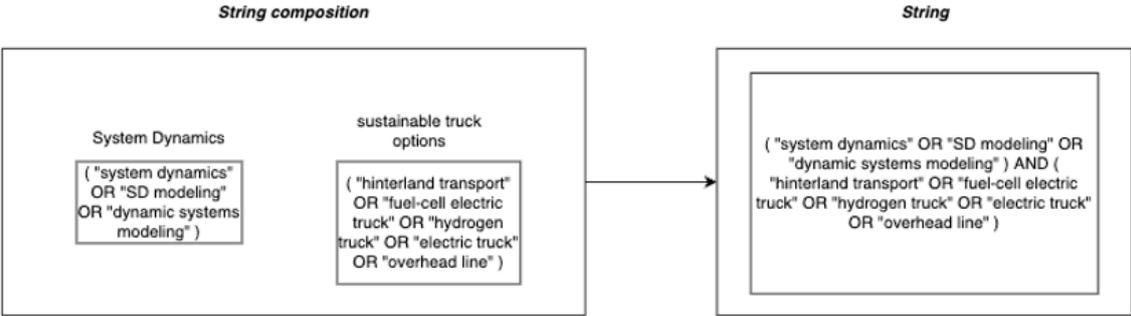


Figure A.4: Literature research round 4

In total, 37 sources were found. From these results it shows that System Dynamics is a more recent method to research the worldwide frontrunner ports, like the large ones in China (Shanghai and Shenzhen). Also, no research from this search has been aimed at the port of Rotterdam.

B

Interview principles and results

B.1. Ethical guidelines

Strict ethical guidelines were adhered to in this investigation to safeguard the integrity of participation. Prior to the collection of data, all interviewees provided written consent after being fully informed about the goals and methods of the study. Participants were informed that participation was entirely voluntary and that they could withdraw or choose not to respond to any questions. To maintain secrecy, no personal information that could lead to the identification of the interviewee was utilized in the thesis text and transcripts. Individual identities would not be disclosed in reports or publications, according to the consent form. All interview transcripts and recordings were kept on encrypted devices with restricted access by the thesis committee in accordance with data protection regulations.

B.2. Reflexivity

In order to maintain the integrity of his research, the researcher used reflexivity and acknowledged his positionality. In order to be reflexive, the researcher had to constantly consider how his experiences, presumptions, or research on truck hinterland transport would affect conversations and interpretations (Berger, 2015). Qualitative researchers need to take into account their "position" in relation to the participants and subject matter, including the power dynamics between local stakeholders and external researchers (Berger, 2015). In order to reduce participant bias and interpret results honestly, the researcher specifically took these elements into account. Throughout this investigation, high standards of research ethics and integrity were upheld by these precautions as well as with truthful and open reporting.

B.3. Expert reflections on carbon intensity of energy reducing technologies

Quote

"Everything is positive right now in the adoption, but there are some negative factors as well that could impact the system. Like the mistrust effect."

Interview 1

"In my next paper I will go more deeply into the price of electricity and how it's determined and try to make a system dynamic model to replicate the reality of the system."

Interview 1

"So it's kind of chicken and egg problem. They are waiting for more trucks and trucks are waiting for more stations."

Quote

Interview 1

"In my model I calculate whole energy demand and divide it by the capacity of 1 station. And then this is the least number of stations that you need."

Interview 1

"In Sweden upgrading the grid is kind of a national governmental thing, so it's not like a private company would intervene there and build charging infrastructure. It can take 10 years to operate the grid and then it could hinder and delay that option of electrical trucks."

Interview 1

"Based on what I found in collaboration with some researcher in Sweden, they said that even for battery and hydrogen, their lifetime is something like 14 years. Then they will be exporting this technology to other countries as well."

Interview 2

"The good of hydrogen is for some applications. For example the long-haul heavy freight that need to travel 1000 kilometers a day, they don't have time to stop for 45 minutes."

Interview 2

"We need to use hydrogen, we need to use BETs, but we need to find the trade-off between these technologies. We can not say that they are competing with each other, they are complementary technologies."

Interview 2

"Public charging is much more expensive than charging in a depot."

Interview 2

"I expect mandatory percentages of renewable fuel to go up gradually."

Interview 3

"E-diesel is 6 to 9 times as expensive as the fossile reference. Biofuels are a factor 3 higher than fossil, so there is a large price difference that biofuels will keep filling."

Interview 3

"CAPEX for hydrogen is three times higher than expected previously. Not considering electricity price hydrogen prices are already estimated much higher now."

Interview 3

"You do not need specific infrastructure specifically for e-diesel."

Interview 3

Table B.1: Expert reflections on carbon intensity of energy reducing technologies

B.4. Expert reflections on validation

Quote

“Quite some transport companies are not able to have charging infrastructure for their fleet at their own location, so parties become dependent on one another and dependent on the public offering of charging infrastructure.”

Interview 4

“At our truck parking that type of trucks spend the night and we are working on constructing charging infrastructure there, which will take a couple of years.”

Interview 4

“Electricity price is a very large driver. It decides cost per kilometer and price per kilometer is everything in container transport.”

Interview 4

“Everyone who owns a hydrogen truck just wants to have the cheapest hydrogen in their truck.”

Interview 4

“A steel producer that has to make its factory more sustainable is willing to pay more for hydrogen, because you can not lower emissions for that factory with a battery. Therefore, hydrogen will go to the industry.”

Interview 4

“That is also what I get back from the container chain. It is about the cents; if you are one cent cheaper then you win a tender.”

Interview 4

“There are people working on biofuels, but for the longer timeframe you can neglect that.”

Interview 4

“For the short-term you might as well use linear extrapolation. For the longer term a System Dynamics model is useful because you can not assume growth will be the same as the year before.”

Interview 5

“At the moment you almost only see Volvos in the most heavy category of trucks, because for a long time that was the only brand that was available.”

Interview 5

“We try to plan trucks to empty out their battery in a day so they can charge overnight. Most trucks stand still at night.”

Interview 5

“Making green hydrogen is an energy intensive process that can not develop above a certain theoretical efficiency.”

Interview 5

“The fleet-centred model for the Port of Rotterdam aligns with your problem formulation, but there is potential to make the model more general and then you use it in another context at the EU-level.”

Interview 6

Quote

"I would put the TCO in a different module because I think that it helps for the reader to understand."

Interview 6

"Emission also can motivate like a public investment, for example in the different green things like charging or like a subsidy or retail or whatever. But you do not need it for your model and that is a future work suggestion."

Interview 6

"The ageing can also be used for implementing different properties for the different ages, for example with operational cost."

Interview 7

"Trucks operating in the forestry industry have only two hours to refuel in between 11-hour shifts, but for container hinterland transport overnight depot charging could work."

Interview 7

"You need to be aware that with the 2050 timeframe I mean it might even be a new new type of attractive technology that we don't know about for now"

Interview 7

Table B.2: Expert reflections on model validation



Model parameter selection

C.1. Model parameter selection

Table C.1 displays the central model variables, accompanied by their values and ranges. Variables discussed in Section 4.4 as part of the literature research for energy efficiency and lifecycle costs are not repeated in this Appendix. Explanation of LOOKUP variables has been omitted; where relevant, they are discussed in Section 5.4 or can be found in the model.

Table C.1: Model parameter values, descriptions, and sources

Variable name	Sub-model	Type	Unit	Description	Base / Initial	Range	Reference
Lifetime BET	Adoption of lower-emission trucks	Constant	Year	Years of operation for a battery electric truck	12	-	(Noll et al., 2022)
Lifetime FCET	Adoption of lower-emission trucks	Constant	Year	Years of operation for a fuel cell electric truck	12	-	(Noll et al., 2022)
Lifetime diesel truck	Adoption of lower-emission trucks	Constant	Year	Years of operation for diesel truck	8	-	(Bhoraskar & Mulder, 2023)
Additional yearly costs	Adoption of lower-emission trucks	Constant	Euro/Truck/Year	Additional TCO costs (driver, tyres, maintenance, tolls, insurance, taxes)	94074	-	(CNR, n.d.)
Discount rate	Adoption of lower-emission trucks	Constant	Dmnl	Yearly depreciation rate of truck value	0.07	-	(Raofi et al., 2025)

Variable name	Sub-model	Type	Unit	Description	Base / Initial	Range	Reference
Mtkm per truck	Adoption of lower-emission trucks	Constant	Mton·km/Truck/Year	Annual freight work per truck for PoR hinterland transport	0.4776	-	Assumption based on total hinterland transport (Lechtenbömer et al., 2018), total Mtkm transported in The Netherlands (Statista, 2024) and total tractor-trailer fleet in The Netherlands (Statista, 2023)
R&D total maturity spending BET	Adoption of lower-emission trucks	Constant	Euro	Total investment to reach full maturity	$5 \cdot 10^7$	-	Assumption to reach maturity in 10 years, based on (Raofi et al., 2025)
Time to spend R&D funds	Adoption of lower-emission trucks	Constant	Year	Investment period for R&D maturity growth	3	-	(Raofi et al., 2025)
Yearly percentage knowledge lost	Adoption of lower-emission trucks	Constant	Dmnl	Annual fading of accumulated R&D knowledge	0.01	-	(Raofi et al., 2025)
Initial maturity BET	Adoption of lower-emission trucks	Initial	Dmnl	Initial technological maturity of BET in 2025	0.3	-	(Raofi et al., 2025)
Percentage of revenue spent on R&D	Adoption of lower-emission trucks	Constant	Dmnl	Share of revenue reinvested in R&D	0.05	-	(Raofi et al., 2025)
Battery size BET	Adoption of lower-emission trucks	Constant	kWh/Truck	Battery capacity of a BET	300	-	(International Energy Agency, 2025)
Percentage new of adopted trucks	Adoption of lower-emission trucks	Constant	Dmnl	Share of new trucks among all diesel truck adoptions	0.72	-	(Bhoraskar & Mulder, 2023)
Cobb Douglas diesel truck	Adoption of lower-emission trucks	Constant	Dmnl	Attractiveness of diesel truck in 2025	1	-	(Raofi et al., 2025)
Initial maturity FCET	Adoption of lower-emission trucks	Initial	Dmnl	Initial technological maturity of FCET in 2025	0.1	-	Assumption based on Section 4.2.2 and other initial maturity levels from Raofi et al. (2025)

Variable name	Sub-model	Type	Unit	Description	Base / Initial	Range	Reference
Battery size FCET	Adoption of lower-emission trucks	Constant	kWh/Truck	On-board battery for FCET	70	-	(Earl et al., 2018)
Discount rate BET	Charging infrastructure BET	Constant	Dmnl	Yearly depreciation of BET charging infrastructure	0.1	-	(Noll et al., 2022)
Lifetime of station BET	Charging infrastructure BET	Constant	Year	Lifespan of a BET charging station	8	6–10	(Raofi et al., 2025)
Percentage of CAPEX to calculate OPEX	Charging infrastructure BET and Charging infrastructure FCET	Constant	1/Year	OPEX proxy based on CAPEX	0.05	-	(Raofi et al., 2025)
Construction cost electric charging station	Charging infrastructure BET	Constant	Euro/Station	Cost of building one BET charging station	20576	-	Calculation based on price per kW from Raofi et al. (2025)
Construction cost hydrogen charging station	Charging infrastructure FCET	Constant	Euro/Station	Cost of building one hydrogen charging station	2.126.000	-	(Nolte et al., 2024)
Fraction profit per kWh delivered	Charging infrastructure BET	Constant	Dmnl	Profit margin on delivered electricity	0.5	-	Assumption
Planning horizon	Charging infrastructure BET and Charging infrastructure FCET	Constant	Year	Projected future years for investment decision	5	-	(Raofi et al., 2025)
Timeframe of average	Charging infrastructure BET and Charging infrastructure FCET	Constant	Year	Past years considered in investment decision	3	-	(Raofi et al., 2025)
Maximum charging capacity of a station per year	Charging infrastructure BET	Constant	kWh/Station/Year	Maximum annual delivery capacity of a BET station	385440	-	Calculation including hours in year and capacity of alternate current charging station
Maximum charging capacity of a hydrogen station per year	Charging infrastructure FCET	Constant	kg/Station/Year	Maximum annual delivery capacity of a FCET station	127750	-	(Nolte et al., 2024)

Variable name	Sub-model	Type	Unit	Description	Base / Initial	Range	Reference
Time to build a charging station	Charging infrastructure BET	Constant	Year	Construction time for BET station	2	-	(Reel, 2022)
Time to build a hydrogen station	Charging infrastructure FCET	Constant	Year	Construction time for FCET station	2	-	Assumed same as construction time of a BET charging station
Lifetime of a hydrogen charging station	Charging infrastructure FCET	Constant	Year	Lifespan of FCET charging station	8	-	(Wulf, 2012)
Fraction profit per kg H ₂ delivered	Charging infrastructure FCET	Constant	Dmnl	Profit margin on delivered hydrogen	1.4	-	Assumed high due to high OPEX
Initial charging stations	Charging infrastructure BET	Initial	Dmnl	BET stations in PoR in 2025	1	-	Initialized at 1 to start adoption loop
Initial hydrogen charging stations	Charging infrastructure FCET	Initial	Dmnl	FCET stations in PoR in 2025	1	-	Initialized at 1 to start adoption loop
Price elasticity	Truck hinterland transport	Constant	Dmnl	Elasticity of Mtkm to transport price per Mtkm	-1	-	(De Jong, 2010)
Initial demand	Truck hinterland transport	Initial	Mton·km/Year	Freight demand for PoR hinterland transport	13700	-	(Lechtenböhrer, 2018)
Average distance truck transport	Truck hinterland transport	Constant	km	Avg. distance for hinterland truck transport	129	-	(Lechtenböhrer, 2018)
Average payload tractor-trailer	Truck hinterland transport	Constant	Mton	Payload per trip for hinterland truck	$1.1756 \cdot 10^{-5}$	-	(Ligterink & TNO, 2015)



Verification and validation

This Appendix provides the tests that were performed for verification and validation of the system dynamics model of truck hinterland transport. A summarized section covering the key takeaways is given in Sub-section 5.5.1. First of all, verification is performed based on three different aspects. Next, structure of the model and model behaviour of the model are validated with several tests prescribed by Auping et al. (2024), independently by the researcher as well as in conclave with experts.

D.1. Verification

A number of verification tests are carried out to make sure the model is implemented accurately and matches the conceptual model that was previously developed. Prior to validation, verification focuses on determining whether the model has been correctly coded and whether it functions as intended. This stage is essential for ensuring the model's internal consistency and avoiding mistakes that can jeopardize the accuracy of simulation results. Correct model coding, dimensional analysis, and numerical error detection are the three main categories of verification tests that are outlined in the paradigm put forth by Auping et al. (2024). The majority of the verification was done while the model was being built. Verifying equations, testing individual components methodically, and ensuring compliance with the basic design were all necessary to ensure the accuracy of the coding.

D.1.1. Correct model coding

The validation of the flow *Truck Fleet Inflow* was one important verification that resulted in a model adjustment. This variable ought to only lead to an increase of the number of trucks in the Port of Rotterdam truck fleet when cargo flow demands this. The initial coding of the flow, however, became negative if cargo flow was reduced, thereby decreasing the size of the Port of Rotterdam truck fleet. The assumption in this model is that trucking companies do a truck long-term investment decision based on an economic valuation for a certain number of years, which excludes the option to simply discard trucks when less cargo for transport is available. This was fixed by including in the *Truck Fleet Inflow* equation an IF THEN ELSE function, which only allows for a positive inflow of trucks. The model also includes a number of stock variables that are measured on a scale of 0 to 100%. This is true for the stock of *BET Maturity*, which is why a floor was installed at 0 using a MAX function. Furthermore, no exceedances of the 100% maturity level were possible due to the addition of the *Maturity gap* variable, which by multiplication with the *Normalized BET knowledge* resulted in multiplication with 0 if the maturity was 100% and no further gap existed. Lastly, It was verified that all stocks react as anticipated by experimenting with different input scenarios and integrating empirical findings, guaranteeing the consistency and dependability of the model.

D.1.2. Dimensional consistency analysis

In order to guarantee that equations are conceptually and technically sound and to avoid unit mismatches that might result in inaccurate model behaviour and deceptive outcomes, dimensional consistency is also crucial in dynamic modeling. Given that the model consists of different submodels, focusing on different aspects of the decarbonisation effort in the Port of Rotterdam truck hinterland transport, close attention was paid to dimensional consistency. For example, the variable *Annual Carbon Emissions ICE* in the emissions submodel calculates carbon emissions per kilometer, while the variable *Transport price per Mtkm* in the Hinterland transport submodel bases its calculation on kilometers in combination with a payload that is transported for this distance. These differences were addressed by using many extra variables and shadow variables that explicitly show the calculation of model values that are expressed in different units. The unit-check function that is built into the System Dynamics software Vensim was used to confirm dimensional consistency, and was utilized until it found no more dimensional mistakes. SI-prefixes were chosen at the same level, so that the Vensim unit-check function did not raise errors. Calculating the variable *Annual carbon emissions ICE* in grams does produce a very large number if it is expressed in grams, but since the variable *ETS2 CO₂ pricing* calculates the carbon

price per gram a balance had to be struck for an SI-prefix that can bring these variables together for joint calculation.

D.1.3. Numerical errors

When running a model, two types of numerical errors may occur: model-dependent errors and method-dependent errors. While model-dependent mistakes arise from improper model construction, method-dependent errors are caused by the integration method and time step selection. It was verified that there are no model-dependent mistakes by debugging the model while comparing varied outcomes with expected behaviour, or the lack of erratic behaviour. For this model, the Euler integration method was selected with a time-step of 0.125 (with time unit Year), as was previously mentioned. Models having IF THEN ELSE functions, or discontinuous models, are best suited for the Euler technique.

D.2. Validation

Several tests have been performed to test whether the model is fit for its purpose of modelling the adoption of carbon intensity of energy reducing technologies. For testing model structure, a structure-verification test, parameter-verification test and boundary-adequacy test have been done with face validation by experts. Also, extreme conditions-tests have been performed. Next, to test model behaviour sensitivity analyses have been utilized.

D.2.1. Boundary-adequacy test

For the sake of assessing whether a system dynamics model is fit for purpose it should include the required structural relationships, for which purpose a boundary-adequacy test is performed (Auping et al., 2024). For this model the boundary-adequacy test was performed with 4 different experts through face validation. These experts come from different backgrounds and hence present different perspectives on the structural relationships that drive the adoption of lower-emission truck technologies. The following questions and a synthesis from the responses are given underneath.

Do the chosen submodels (truck renewal, hinterland transport, charging infrastructure and energy source availability) contain the essential elements to base decision-making about adoption of lower carbon intensity of energy technologies?

All interviewees agreed with the inclusion of the chosen submodels, since they have a significant impact on the adoption of lower carbon intensity of energy technologies. Furthermore, it was stressed that these submodels are independent and should be regarded jointly in a model, to accurately model chicken-and-egg dynamics present in the system of truck hinterland transport.

Do you see any other important factors that could play a role?

Electricity price was mentioned in multiple interviews as vital to the decarbonization of truck transport. It forms a large component of the TCO of BETs, according to all interviewees the most promising carbon intensity of energy reducing technology. The dynamics that shape the electricity could have formed an interesting addition to the model. However, the depot style of charging in the central transport node of the Port of Rotterdam that was chosen for this research means that this remains outside of the scope. In order to still mitigate the risk of overlooking essential electricity price sensitivity, large electricity price fluctuations were researched in the extreme conditions test in Appendix D.2.5.

Is the timeline until 2050 a useful mid-term analysis timeframe for the adoption of new carbon-content of energy reducing technologies for trucks?

In the interviews it was stressed that 2050 forms a clear beacon that is clearly aligned with emission reduction goals at the international level and of individual organisations like the Port of Rotterdam. Therefore, the research process is strengthened by an abundance of research focusing on the same targets for 2050, that can provide reliable information to base the model on. This was experienced during the literature research, for example by the retrieval of quantified scenarios that could be used in the scenario analysis.

A relevant remark in relation to the timeframe was that by looking only at a specific set of technologies for a period of several decades, new emerging technologies that could seriously compete in the long-run are overlooked. The example of a hydrogen internal combustion engine truck was tabled, a technology of adapting the motors of existing internal combustion engine diesel trucks to the use of hydrogen. The researcher acknowledges this point, while realizing that a selection of technologies had to be made in order to assure the required depth in the literature research into the specifics of the technology and its adoption. This selection was made specifically for the Port of Rotterdam based on research that was specifically performed in this context (Lechtenböhmer et al., 2018). Furthermore, the research started off with the assumption that adoption to a lower carbon intensity of energy technology required the adoption of a new truck (except for the use of e-diesel), thus relying on large

investment decisions from trucking companies that increase the maturation time for the emerging technologies. This was deemed to not be possible in the 25-year timeframe for technologies that not appeared promising at the start of this research. However, the researcher does encourage further research to include other technologies, for which the system dynamics model from this research can be expanded. The Cobb Douglas function that defines the adoption choice between different truck alternatives can be redefined so that it makes a trade-off that includes another option. Also, when dealing with a technology that retrofits an existing diesel truck - such as the hydrogen internal combustion engine - an extra ageing chain can be created, that the truck leaves the existing diesel truck ageing chain for in case it is retrofitted.

Is the focus on a specific energy hub such as the Port of Rotterdam, focusing on ‘their’ aggregated fleet, a useful one?

Respondents validated the importance of looking at specific examples, that show the specific dynamics between operationalized submodels involved in the adoption of lower carbon intensity of energy technologies. A clear problem has also been formulated for the Port of Rotterdam due to rising container transport by truck, so it is appropriate to address that specifically with a tailored model. Lastly, the usability of the model in similar contexts was deemed valuable. The research could be repeated for another port closeby, so that one by one energy hubs can lower their carbon emissions based on evidence and thorough knowledge of the dynamics at play.

Would it be acceptable to trucking companies to exclude fast charging and focus on alternate current depot charging in the Port of Rotterdam?

With the scope of this research being on the specific example of the Port of Rotterdam, the choice for depot charging was validated. Mandatory breaks for truck drivers were highlighted as opportunities for undergoing the longer charging time required for alternate current charging. A more expansive look on charging infrastructure, including public charging stations along the road, require a national approach that also deals with the spread of these stations, as has been done for Germany (Speth & Plötz, 2024). Lastly, it was mentioned that charging breaks in the forestry industry are only two hours and would not be compatible with this style of charging, but that alternate current depot charging would align with some truck segments active in container hinterland transport in the Port of Rotterdam.

Further relevant answers from the interviews related to structural relationships in the model have been cited as quotes and documented in Appendix B.4.

D.2.2. Structure-verification test

The structure-verification test is used to assess whether model structure is not in contradiction with the real world system (Auping et al., 2024). This test was performed continuously in the modelling process, during which new knowledge was constantly challenging the existing assumptions about system structure. When completed, face validation by experts was used to assess model structure once more. The structure-verification focused on validating feedback loops that stemmed from a single source in literature, for which the validation by other experts proved a valuable assurance for the use of these feedback loops. The following feedback loops were validated in the interviews by asking the questions:

Do you recognize the reinforcing feedback loop of technology awareness?

This feedback loop was recognized by experts in the interviews. The definition of awareness as a fraction of the total truck fleet was found to not fully cover awareness, but it was found to be a sufficient definition in the light of a fleet-centred model.

Do you recognize the reinforcing feedback loop of technology maturity?

This feedback loop was recognized by experts in the interviews, as long as specific technological improvements that accompany improved maturity are also explicitly modelled. That is because these factors drive TCO in the model, with maturity not directly linked to TCO in the model at hand. An explicit improvement for BETs has been modelled by defining decreasing battery costs with a LOOKUP function. In one interview it was also addressed that the increased maturity of truck types has additional side-effects. It does not merely lead to an increased attractiveness of a technology type. It can also influence its energy efficiency during its lifetime. The ageing chain in the system dynamics model can be utilized for implementing these different levels of energy efficiency. However, this does require an extra research and brings with it a lot of uncertainty that the aggregated factors in this model manage to avoid.

Do you recognize the balancing feedback loop Fleet dependent transport price (B5) (Transport price per Mtkm -> Hinterland truck transport -> Hinterland truck fleet size -> TCO truck fleet)?

This balancing feedback loop was agreed on by experts. An important issue is that it does not consider average TCO per truck, which can lower or increase due to the adoption of new truck types. However, the separate

feedback loop Price effect of decarbonization (FBL6) has also been identified in the model and does include this effect on average TCO per truck. Therefore, this macro-effect fleet increase that mitigates decreased transport cost can co-exist with the more specific Price effect of decarbonization (FBL6). The feedback loop only being activated when an increase in cargo throughput initiated the price elasticity was also validated, given that truck investment costs are long-term decisions and trucks are not easily discarded from a truck fleet.

Further relevant answers from the interviews related to the alignment of feedback loops from the model with the real world have been cited as quotes and documented in Appendix B.4.

D.2.3. Parameter-verification test

The parameter-verification test assesses whether the parameters used in the model correspond to their values as they can be observed in the real-world system (Auping et al., 2024). The literature search has attempted to be thorough in selecting objective and up-to-date parameter information. Parameter information was taken from environments similar to the Port of Rotterdam, for example those that are geographically close. Furthermore, since the carbon-content of energy reducing technologies are developing rapidly, up-to-date information from 2020 and older has been preferred where possible. Also, ranges have been constructed for parameters by combining different sources, over which the average value has been utilized in the system dynamics model. Lastly, two parameter values that remained unsure have been validated in the expert validation sessions with the following questions:

Do you agree with PBL and TNO reports that green hydrogen will not become cheaper than grey hydrogen before 2050?

Respondents agreed with these research findings, highlighting the ceiling of energy efficiency that the energy-intensive process of green hydrogen production is characterized by.

Do you agree with weights used for decision-making of new truck adoption: maturity 0.2, awareness 0.5 and charging station availability 0.3?

The importance of factors, expressed by the corresponding weights, was agreed on by the experts. Especially, when it was clarified that the low weight of maturity was compensated for by explicit cost-reducing improvements in the model that influence TCO. Furthermore, although these weights construct the Cobb Douglas value in the model that is compared with yearly TCO in order to calculate the attractiveness of the technological alternative, it was dubbed to give yearly TCO an even greater contribution. TCO was deemed very important in the tight container transport market, but in this model the choice has been made to use Cobb Douglas to show the interdependence between subsystems that allow for lower-emission truck adoption.

Further relevant answers from the interviews related to parameter validity have been cited as quotes and documented in Appendix B.4.

D.2.4. Extreme conditions tests

The extreme conditions test evaluates the model equations under extreme conditions (Auping et al., 2024). Extreme conditions produce predictable behaviour in the real world that the model should reproduce in order to be 'fit for purpose' (Auping et al., 2024). Table D.1 shows the parameters that have been chosen for extreme conditions test. The extreme conditions test is performed directly for two relevant input variables. After comparing each extreme scenario to a standard base case, the behaviour that results is thoroughly examined and addressed.

Input Variable	Base Case	Min Value	Max Value
Carbon intensity diesel	1618	0	5000
Lifetime BET	12	1	45

Table D.1: Parameter settings for extreme conditions tests

Extreme conditions for carbon intensity of diesel

The results of the extreme conditions test for extreme scenarios of carbon intensity of diesel are shown in Figure D.1-D.4. It shows that the carbon intensity of diesel does not drastically influence adoption behaviour; the adoption of both BETs and FCEs only fluctuates by a couple percent by 2050. Because of that, the amount of installed charging stations or the fraction of energy used does also not change much for both modalities. This highlights that the ETS2 tax on carbon emissions for diesel trucks that are almost minimized in the min-scenario and extremely high in the max-scenario, is not the major driver of yearly TCO. Extreme taxation in the min

and max scenario does not lead to a drastically reduced attractiveness of diesel trucks that would lead to more adoption of lower-emissions truck types. This finding aligns with the partial role that ETS2 taxation plays among other relevant TCO costs, which is amplified by the fact that trucks only drive around 40.000-50.000 km in the model because only their Port of Rotterdam truck hinterland transport trips are included. The impact of changes in fuel cost due to carbon-emission taxation could be more significant if a higher number of yearly kilometers per truck is taken into account.

Moreover, the validity of the model is validated by the drop of total CO₂-emissions in the min-scenario to a marginalized fraction of the total CO₂-emissions in the base case. Since about half of the truck fleet is still a diesel truck in 2050 and these diesel trucks are emitting no carbon-emissions, the contribution of this most heavily polluting truck type to total CO₂-emissions is subtracted. It can be concluded that total CO₂-emissions are calculated correctly from the model.

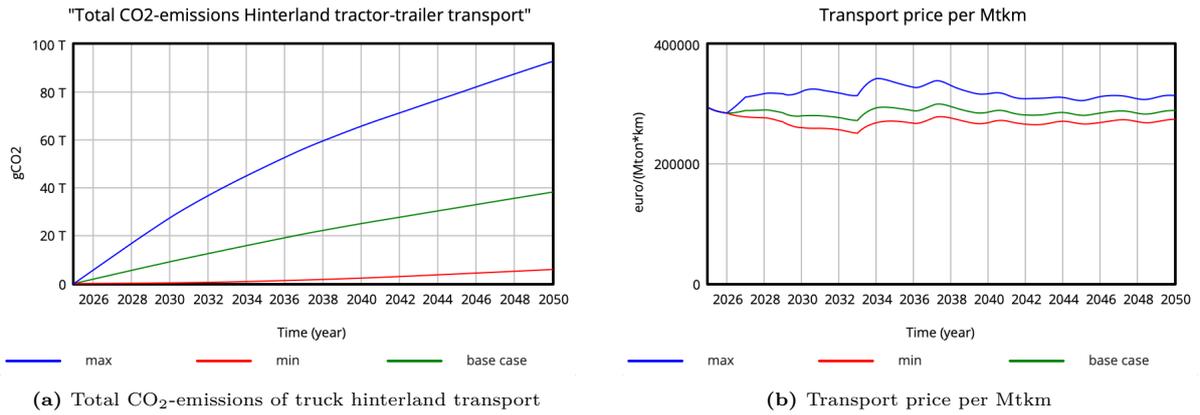


Figure D.1: First two KPIs under extreme conditions of carbon intensity of diesel

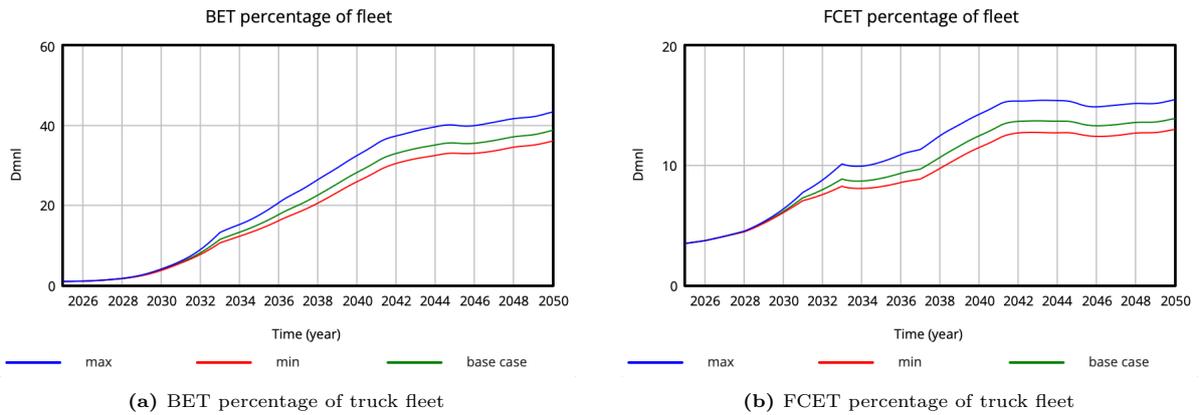


Figure D.2: Second two KPIs under extreme conditions of carbon intensity of diesel

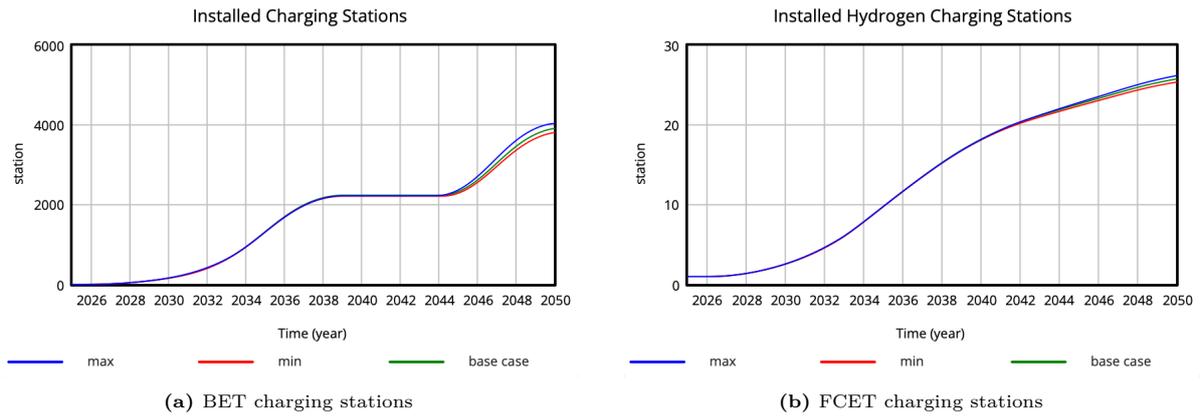


Figure D.3: Third two KPIs under extreme conditions of carbon intensity of diesel

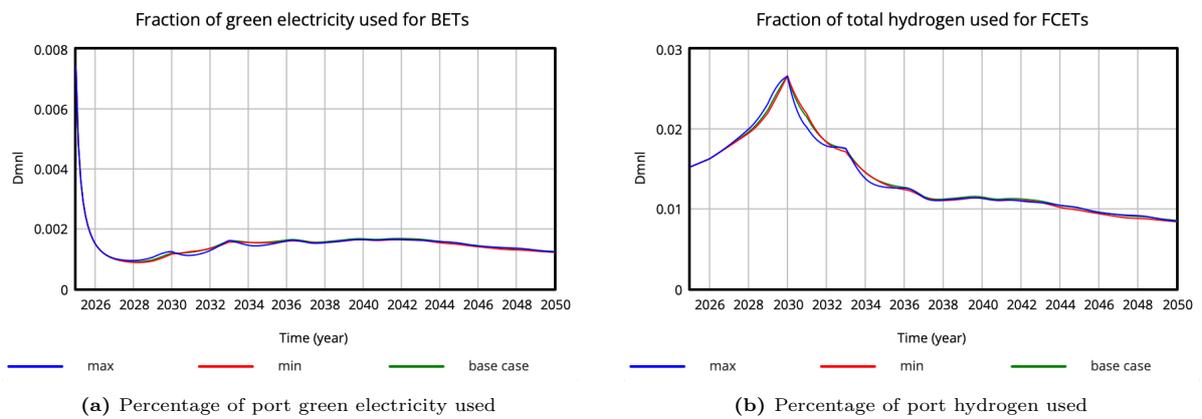
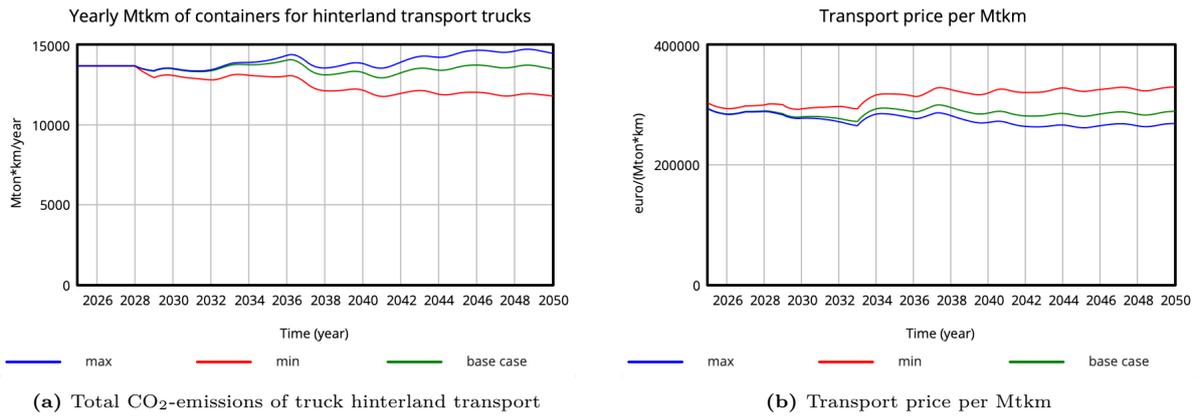


Figure D.4: Fourth two KPIs under extreme conditions of carbon intensity of diesel

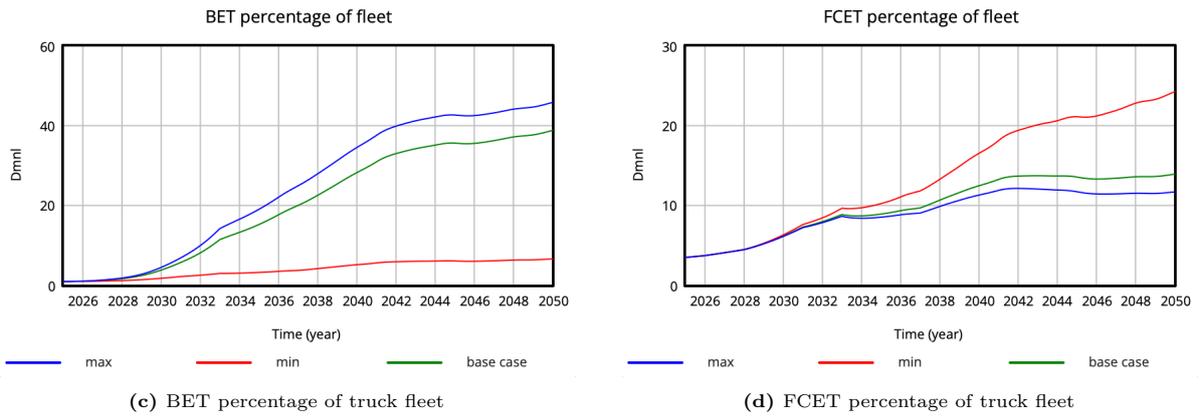
Extreme conditions for lifetime BET

A second extreme conditions test was performed by varying the lifetime of a BET. Yearly TCO is calculated over the lifetime of a BET, so this parameter variation is expected to significantly impact attractiveness of the BET. That is because the BET has a high initial cost that investors would want to spread out over multiple years of driving. The results of this extreme conditions test are displayed in Figure D.5.

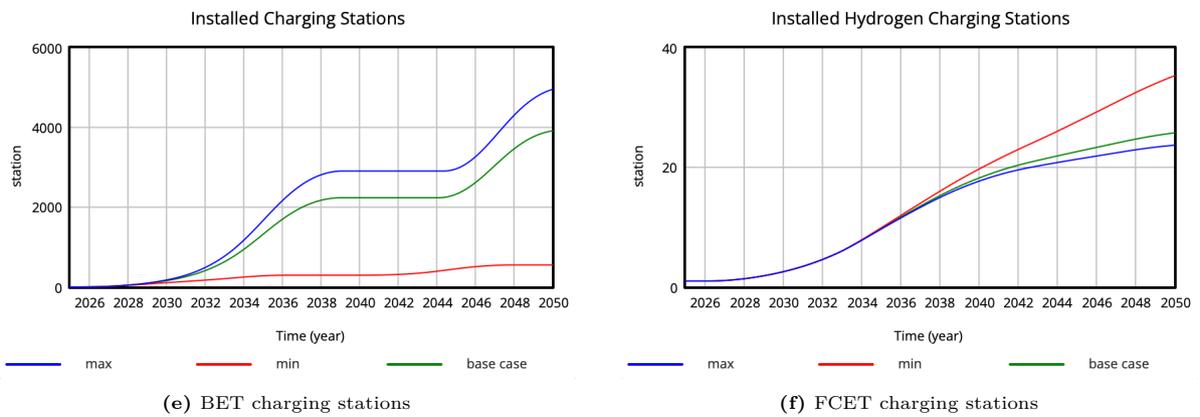
As expected, in the min-scenario the market share of BETs drops to about a fifth of its base case value to 8 percent. Not all market share is lost, due to its existing maturity, awareness and charging infrastructure. The market share lost by BETs is taken over both by FCETs and diesel trucks. The market of charging infrastructure for BETs shows a valid respond to this decreasing market share of BETs, by constructing a fraction of the number of charging stations from the base case. Interestingly enough, the max-scenario does not generate a truck fleet that consists merely of BETs. Instead, only a marginal increase in comparison to the base case is realised, highlighting that yearly TCO is only one of the deciding factors for truck adoption in this model.



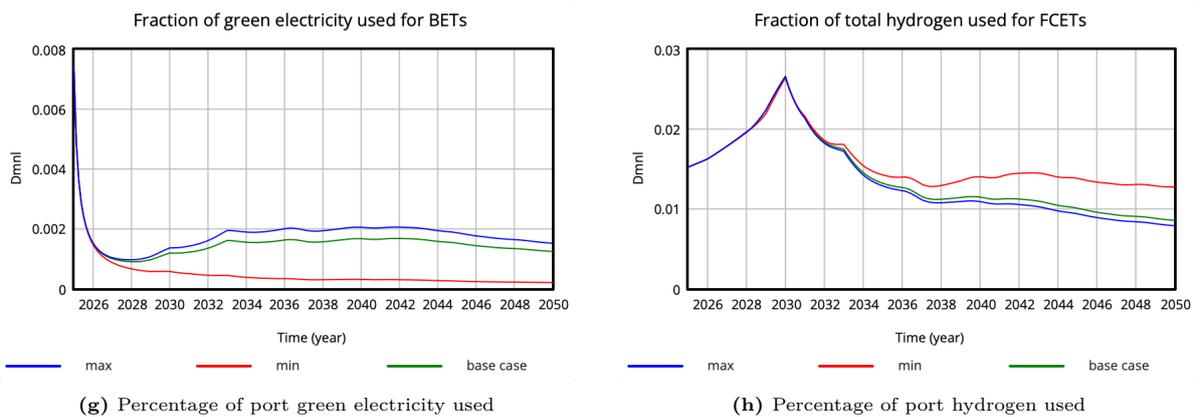
First two KPIs under extreme conditions of lifetime BET



Second two KPIs under extreme conditions of lifetime BET



Third two KPIs under extreme conditions of lifetime BET



Fourth two KPIs under extreme conditions of lifetime BET

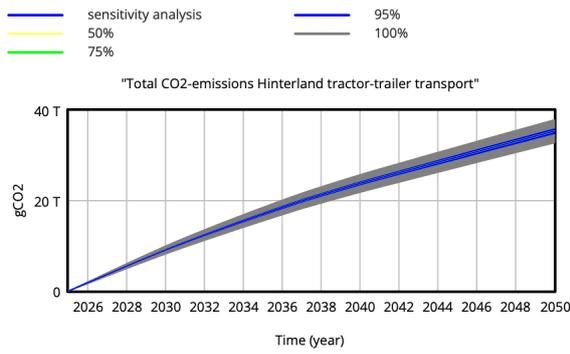
Figure D.5: KPIs under extreme conditions of lifetime BET

D.2.5. Sensitivity analysis

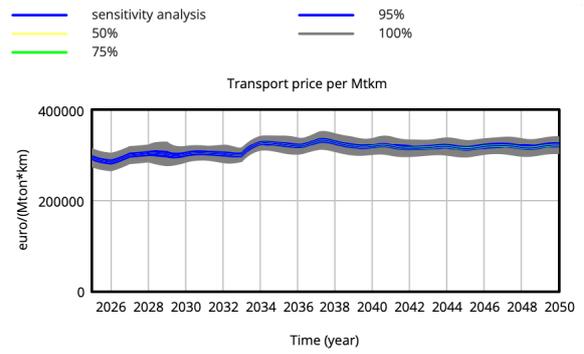
The behavioural validation sensitivity analysis, which evaluates how the model reacts to changes in important parameters, is presented in this appendix. It is usual procedure to add or subtract 10% from a common base case in order to routinely alter parameter values. Two sensitivity analysis methodologies are used, as advised by Auping et al. (2024). First, by concurrently altering several parameters, a multi-variate sensitivity analysis assesses the model's overall sensitivity. A uni-variate sensitivity analysis, on the other hand, looks at the effects of changes in individual parameters. Vensim's sensitivity analysis tool is used to implement both strategies. Latin Hypercube Sampling (LHS), which produces 200 distinct simulation runs, is used to provide reliable and uniformly dispersed sampling.

Multi-variate sensitivity analysis

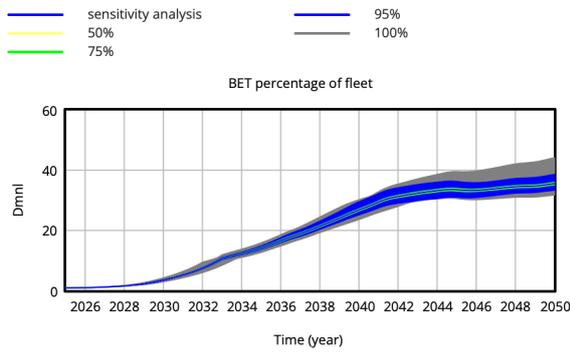
The reactivity of the KPIs of this research to the multi-variate sensitivity analysis is displayed in Figure D.6. It can be deferred that operational KPI's from the Port of Rotterdam are not sensitive to small fluctuations in parameters; *Total CO₂-emissions of truck hinterland transport* and *Transport price per Mtkm* show no large deviations or different behavioural development. This is likely due to the large balancing effect that the feedback loop Fleet dependent transport price (B5) has on the system. When regarding the other KPI's, it is noteworthy to mention that FCET adoption is much more sensitive than BET adoption. The different scenarios from the multi-variate sensitivity analysis result in larger confidence intervals for *FCET percentage of fleet* and *fraction of hydrogen used for BETS*. For *FCET charging stations* some scenarios in the 100% confidence interval even result in no hydrogen stations at all. This is different for the same KPI's for BET adoption, likely because the development of BETs is already further at the start of the modelling time in 2025 and therefore is less dependent on uncertainty.



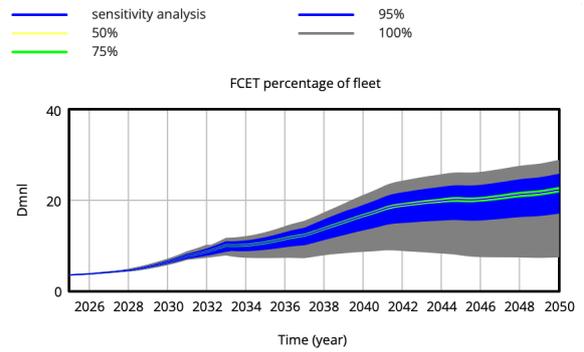
(a) Total CO₂-emissions of truck hinterland transport



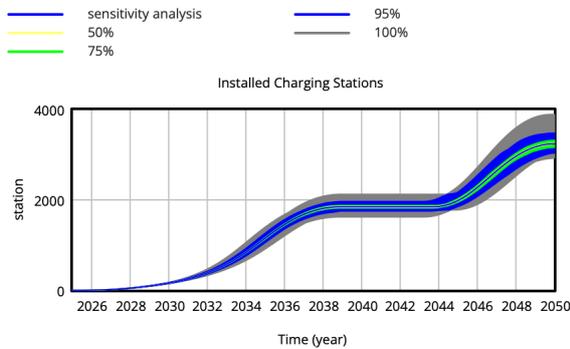
(b) Transport price per Mtkm



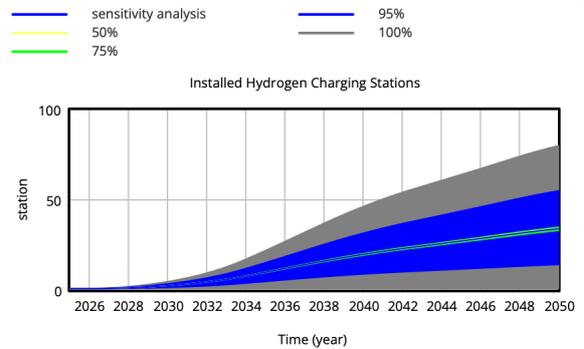
(c) BET percentage of truck fleet



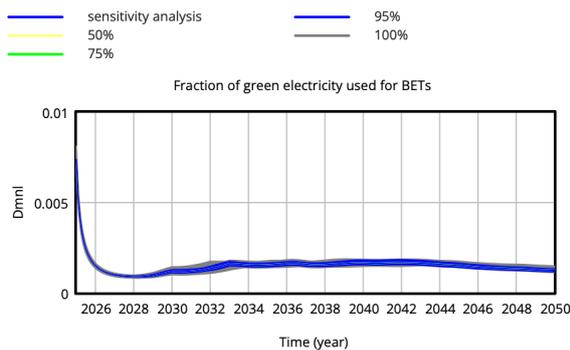
(d) FCET percentage of truck fleet



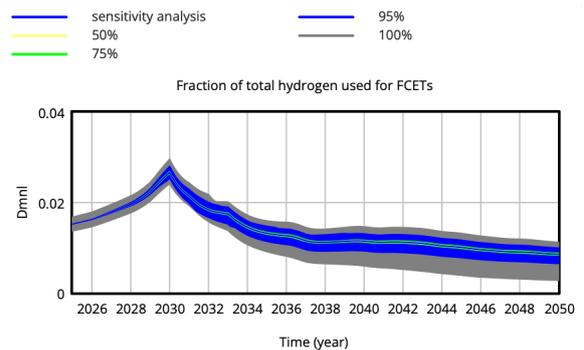
(e) BET charging stations



(f) FCET charging stations



(g) Fraction of green electricity used for BETs



(h) Fraction of hydrogen used for FCETs

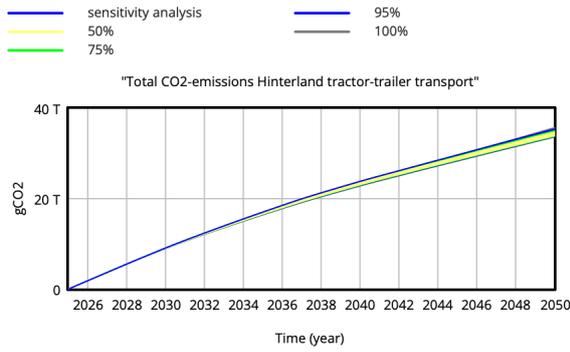
Figure D.6: Performance of KPI's in multivariate sensitivity analysis

Uni-variate sensitivity analysis

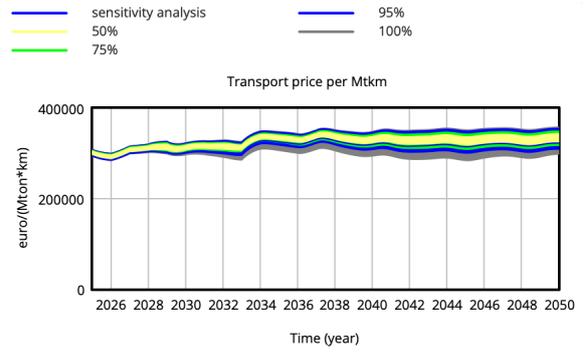
In the interviews it was mentioned that electricity price for fast-charging still carried a large uncertainty, while it is essential for the adoption choice of a BET for a trucking company. Therefore, a uni-variate sensitivity analysis was performed for this constant with larger deviations than the usual 10%. In comparison with the base value of 0.55 euro/kWh, a minimum value of 0.2 euro/kWh and a maximum value of 0.9 euro/kWh were used.

The results of the KPI's from the uni-variate sensitivity analysis from Figure D.7 show that electricity price has a large effect on the adoption of BETs, causing percentual changes in the *BET percentage of truck fleet* and an even larger effect on the number of *BET charging stations*. The negative effect of an increasing electricity price is larger than the positive effect of a decreasing electricity price on *BET percentage of truck fleet* and *BET charging stations*.

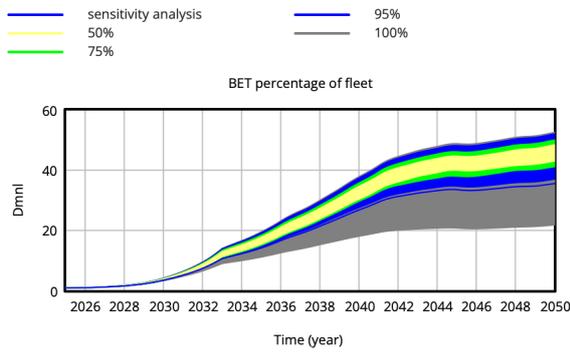
An interesting effect of decreased market share of BETs due to a higher electricity price, is that the increase in *FCET percentage of fleet* is larger than the decrease in *BET percentage of fleet*. That is characterizable behaviour in this model, where reinforcing feedback loops Word-of-mouth (R2) and R&D cycle (R3) start to have a multiplying effect after a difficult starting phase of the adoption for the FCET-technology.



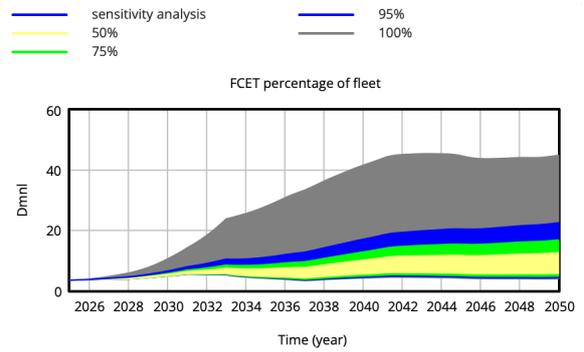
(a) Total CO₂-emissions of truck hinterland transport



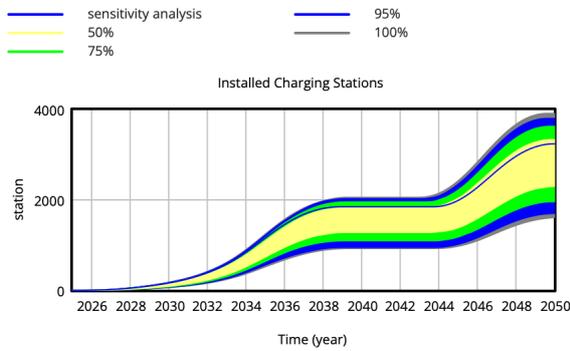
(b) Transport price per Mtkm



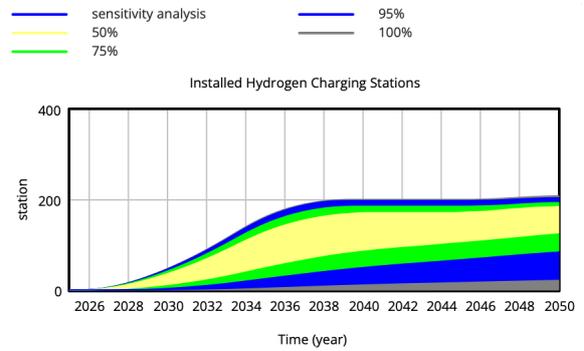
(c) BET percentage of truck fleet



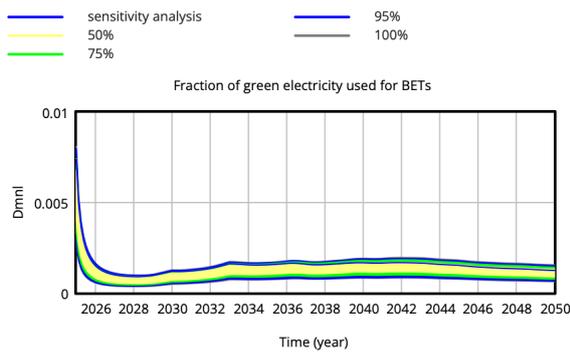
(d) FCET percentage of truck fleet



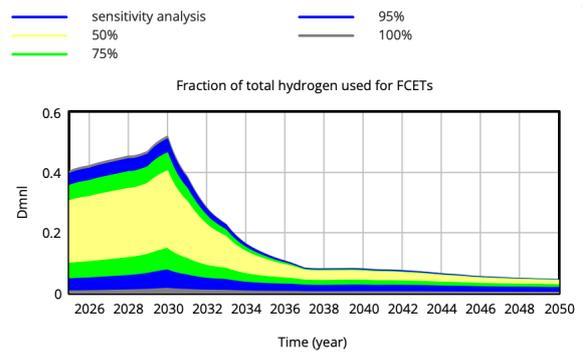
(e) BET charging stations



(f) FCET charging stations



(g) Fraction of hydrogen used for FCETs



(h) Fraction of green electricity used for BETs

Figure D.7: Performance of KPI's in uni-variate sensitivity analysis for varying electricity price



Scenario background

E.1. External driving elements

The four container throughput scenarios offer different perspective on the port and its industrial complex, looking at how changes in society, technology, economics, and geopolitics may affect the amount and make-up of port traffic. Eight main external driving elements form the foundation of the scenario framework:

1. Geopolitical stability
2. Government policy and public spending
3. Consumer behaviour
4. Global climate change measures
5. The shift from a linear to a circular economy
6. Corporate social responsibility
7. Changes in the relative true cost of production
8. Changes in the relative true cost of transportation

For the future of the port-industrial complex, its clients, partners, and the Port of Rotterdam Authority itself, these factors are the most unpredictable and significant. The four conceivable worldwide trajectories toward 2050 that come from the variations in the direction and strength of these factors in each scenario define a range of potential futures for the port.

E.2. Scenario description

The four scenarios and their impact on truck hinterland transport volumes are described in the following subsections.

E.2.1. Connected deep green

This scenario posits a future of robust international collaboration, wherein governments collectively pledge to ambitious climate objectives and increase digital transparency in logistical chains, ultimately leading to global carbon neutrality by 2050. This course limits the rise in world temperatures to 1.5 °C this century and brings about widespread wealth and strong economic growth. This scenario is supported by high institutional quality and geopolitical stability, while substantial investments in carbon neutrality and renewable energy, along with substantial population increase, propel robust GDP expansion. Global trade thrives, leading to significant increases in container handling, while renewable energy replaces fossil fuels as the primary source by 2050.

Due to the presence of a globally interconnected world order and open trade lines, this scenario entails the highest port throughput of 580 Mt. Of this trade volume, 51% consists of container transport volume. When the fraction of container freight transported specifically by trucks (0.76) is applied, a total of 223 Mt of containers are transported by trucks in 2050 in this scenario.

E.2.2. Regional well-being

This scenario is led by a more regional focus on clean and healthy environments, privacy, and well-being emerging in the early 2030s among clusters of nations, replacing the common commitment to global change that is undercut by a lack of sufficient trust. This shift results in moderate economic development and a less favorable business environment for basic industries in Northwestern Europe. Only moderate global economic growth is a result of trade obstacles and disparate countries' carbon reduction policies. The increased focus on environmental quality in Northwestern Europe presents extra hurdles for energy-intensive sectors. While breakbulk volumes increase as a result of higher imports of semi-finished goods, the port and industrial complex saw a steep decline in total

throughput, especially in crude oil, coal, and iron ore. However, shortsea shipping volumes are rising as a result of the strengthening intraregional European market.

Due to less global trade outside of the region, this scenario entails a relatively small port throughput of 430 Mt. In a decarbonizing Northwestern Europe there is less trade of break bulk, so a large percentage of 54% is dedicated to container transport volume. When the fraction of container freight transported specifically by trucks (0.76) is applied, a total of 176 Mt of containers are transported by trucks in 2050 in this scenario.

E.2.3. Protective markets

In this scenario, geopolitical tensions are exacerbated and the successful integration of logistical chains is impeded by a lack of confidence between global powers. With conflicting economic interests and a focus on resilience, financial prosperity, self-sufficiency, and defence, the world becomes fragmented. Economic development continues to be slow, and global carbon neutrality is not reached before 2100. Ignoring climate pledges hurts investment in the port and industrial complex, and productivity is slowed by severe weather and less R&D. A significant decline in throughput volumes results from poor economic performance, which is further exacerbated by a shrinking EU population. Trade restrictions hinder the switch to renewable energy, which leads to a sharp decline in the refining of crude oil. Additionally, when production changes through nearshoring and reshoring, general cargo volumes decline.

Due to less global trade, this scenario entails the smallest port throughput of 400 Mt. Decarbonization is stalling which requires more transport of break bulk, so a small percentage of 44% is dedicated to container transport volume. When the fraction of container freight transported specifically by trucks (0.76) is applied, a total of 134 Mt of containers are transported by trucks in 2050 in this scenario.

E.2.4. Wake-up call

This scenario highlights the important turning point of worry about the economic effects of external shocks, such as disruptions in the supply of food and energy or major weather occurrences. This leads to a stronger understanding of the necessity of strategic collaboration and strict carbon reduction policies. Strong EU policy, modest economic development, and a slow but quick switch to renewable energy are the outcomes of this. This entails more investments and economic growth for the port and industrial complex, which will be fueled by a significant acceleration of renewable energy starting in 2030. This transition is supported by changes in consumer behaviour and attitudes, even though the EU's population is slightly declining. Container volumes rise as a result of the better economic climate and a notable rise in non-fossil fuel throughput.

Due to a moderately growing economy, this scenario results in a port throughput of 520 Mt. 46% is dedicated to container transport volume. When the fraction of container freight transported specifically by trucks (0.76) is applied, a total of 182 Mt of containers are transported by trucks in 2050 in this scenario.



Reflection on the use of AI

I used AI as a support tool during the composition of this thesis, although only sparingly. AI's main function was to quickly scan new or unfamiliar subjects and give me a summary of the main ideas. This assisted me in finding potential reading directions and orienting myself in areas where I lacked prior expertise. In addition, I collaborated with AI to generate structural suggestions. I was able to think of options that would not have come to me right away by experimenting with different formats for arguments or chapters. This was especially helpful early on in the writing process, when the thesis's general structure was still developing. When gaps in the literature review were discovered, AI was also used to recommend possible sources. These recommendations were always regarded as first leads, and I subsequently verified their authenticity, reliability, and pertinence by consulting the original sources directly. Crucially, the arguments and substantive content of the thesis were not produced by AI. Instead, it served as an additional tool to aid in the research process, leaving critical thought, assessment, and final judgment up to me.