Realisation of green freight: a comparative analysis of alternative fuels in road freight transport

Evaluating Electric Battery Trucks, Hydrogen, and Bio-LNG trucks

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Preface

As I present this master thesis, ”*Realisation of Green Freight: A Comparative Analysis of Alternative Fuels in Road Freight Transport*”, my years in Delft as a student at the University of Technology Delft have ended. I reflect on an enjoyable time at the Faculty of Technology, Policy and Management, with this thesis icing on the cake as a personal milestone.

The combination of sustainability and transport, the core of this thesis, has fascinated me during my studies. Much must be done to make the world more sustainable and reduce rising temperatures. However, I have always believed that even small contributions can make a significant impact. It is with this conviction that I present this thesis, hoping it serves as one such contribution towards mission for a more sustainable world.

This journey was not solitary. I express my deepest gratitude to my supervisors, Dr. Ir. P. W. Heijen and Dr. J. A. Annema. The weekly meetings have provided me with guidance to run the process smoothly. Their insights and feedback have been instrumental in shaping the direction and outcomes of this research.

Finally, I would like to thank friends and family, who have been a constant source of support and patience, enduring endless conversations about road freight transport. Your encouragement and interest in my work have been a source of motivation and joy. I have put a lot of energy, effort and fun into this thesis, I hope you will enjoy reading it!

Paula Hamming
Delft, January 2024

Summary

Climate change is an urgent issue; thus, preventing global warming is becoming more prominent on the European political agenda. Greenhouse gas (GHG) emissions are one of the causes of global warming. Among various contributors to GHG emissions, the transportation sector contributes a relatively large proportion of GHG emissions due to the extensive use of fossil fuels. Considerable steps in sustainability have already been accomplished in passenger and urban freight transport. However, long-distance road transport lags in achieving emission objectives.

Heavy-duty trucks (HDT) carry freight by road. To make the industry more sustainable, requirements must be met at the vehicle and infrastructure levels. These requirements make preservation complex. In road freight transportation, three potential types of alternatives can be identified for diesel trucks: Battery Electric Trucks (BETs), Hydrogen trucks and Bio-Liquefied Natural Gas(LNG) trucks. Previous research has focused on comparing the alternatives on a vehicle performance level. This research explores the effect of combining these three alternatives on a network level and determines the impact on the system. This thesis answers the following research question: *"How does combining Electric, Hydrogen, and Bio- LNG heavy-duty vehicles in road freight transport impact the costs and emissions in Europe while ensuring the reliability of the refuelling network, considering technological development, freight growth and limited supply?"* Cost in this thesis refers to financial costs and time costs. A Well to Wheel approach determines the system's CO_2 emissions.

Intervention at the European level by the European Commission (EC) is required to align the public and private interests of the system. The EC, as problem owner, should ensure the realisation of a sustainable, reliable and cost-effective network. In particular, creating incentives among the oil and gas industry and transportation companies is crucial to the transition. To create the right incentives, the understanding of the system and alternatives must be improved. One of the two sides of the market should develop to implement the alternatives successfully; without refuelling infrastructure, transportation companies will not invest, and without demand for fuel, oil and gas companies will not build infrastructure. This research focuses on the development of the refuelling infrastructure. Establishing a reliable infrastructure reduces transport companies' barriers to investments. Therefore, eventually, the entire system's performance improves.

A model is created to improve understanding of the systems' behaviour and answer the research question. In this model, a simulation of European road freight is used to assign freight to one of the alternatives. Subsequently, optimisation by K-means is used to determine the optimal location of refuelling stations for the alternatives. After that, the costs and emissions of the system can be determined.

By varying the model's parameters, combining the alternatives can be explored at the network level. The development of infrastructure can take decades. Therefore, the system must be future-resistant. Thus, the costs and emissions of the system were checked for multiple scenarios. These scenarios include the expected future development of technology and freight demand. In addition, the expected limited supply of alternative fuels is also considered in the scenarios.

Using BETs, Hydrogen trucks (if green hydrogen is used), and Bio-LNG trucks will decrease current system emissions. However, according to this research, combining alternatives for different kilometre range intervals will not be more cost-effective than adopting a singular alternative fuel. Further development of the alternatives reveals the potential for BETs for short- and long-freight trips in terms of costs and emissions. For this, realising MegaWatt chargers and batteries with larger capacities is essential.

Bio-LNG trucks and BETs are considered viable as sustainable fuel options, with Bio-LNG being immediately usable and BETs promising for the future. However, hydrogen as an alternative faces uncertainty due to its current high costs and environmental impact, surpassing even diesel. Without significant advancements in hydrogen technology, the financial and environmental consequences could be severe.

Therefore, the development of hydrogen for HDT freight transport is a risk.

This research mainly sees promise in Battery Electric Trucks (BETs) but advises against excluding other options. Relying solely on one alternative has risks, and the system's reliability may be compromised, as its effectiveness depends on technological advancements. Current EC policy has focused primarily on setting targets. By this research, the understanding of the system has been further increased. Therefore, it is possible to incentivise the system in the desired direction. The policy should focus on actively developing BET infrastructure, including expanding the energy grid, providing conditional funding, standardizing MegaWatt charging stations, and effectively communicating the benefits of different alternatives to stakeholders. Additionally, since vehicle costs are a significant part of total system costs, the EC could encourage the adoption of sustainable trucks by offering subsidies, thus promoting a greener freight transport sector.

This research is consistent with previous research but has contributed to understanding the system. Contrary to expectations, the study shows the future potential of BETs for short and long-haul trips. This thesis has extended the understanding by offering a more integrated analysis of the potential of combining different alternative fuels. Future studies can further examine the effect of technological developments and check the sensitivity of these developments individually. In addition, future studies could focus on a broader perspective of environmental impact.

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List of Acronyms

AFIR	Alternative Fuel Infrastructure Regulation
BET	Battery Electric Truck
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
EAFO	European Alternative Fuel Observatory
EC	European Commission
EV	Electric Vehicle
FRLM	FLow Refueling Location Model
GHG	Greenhouse Gas
HDT	Heavy Duty Truck
LNG	Liquefied Natural Gas
NUTS	Nomenclature of Territorial Units for Statistics
PM	Particulate matter
TtW	Tank to Wheel
VOT	Value of Time
WtT	Well to Tank
WtW	Well to Wheel

1

Introduction

Global warming is a growing problem for global livability, with melting ice caps causing sea levels to rise and more extreme weather. We are starting to the world's vulnerability. The initiatives to keep the world livable are there, such as the Paris Climate Agreement. 196 Parties adopted the Paris Agreement on December 12, 2015. The overarching goal is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels [67]. The goals are there, but achieving them seems to be a considerable challenge. The goals for reducing climate change impacts seem to be unmet, and global temperatures are continuing to rise. The world might be already irreversibly damaged by human activity. Therefore, the goals might already seem unreachable.

1.1. Emissions in freight transport

Greenhouse gas (GHG) emissions trap heat, which causes the earth's temperature to rise. Without greenhouse gases, the earth would be freezing cold, but with too many greenhouse gases, it gets too hot. GHG emissions caused by human activity play a role in global warming. Besides the most well-known GHG emission by carbon dioxide (CO_2), there are three more GHGs: methane (CH_4), nitrous oxide (N_2O), and fluorinated gases(F-gases). CO_2 is often used to measure climate change because it is one of the most common GHGs emitted by human activities. In addition, CO_2 has a long atmospheric lifetime. Therefore, CO2 contributes to long-term climate change.

One of the sectors contributing to GHG emissions is the transport sector. Due to the extensive use of fossil fuels within this sector, its contribution to the overall GHG emissions is high. In passenger transport, a transition can be observed. People are switching their fossil fuel cars to electric vehicles (EVs). In the streets, charging points appear. In addition, EVs are becoming less expensive. This is also due to the subsidies consumers can receive when buying an EV. This makes these cars more accessible to consumers.

However, a considerable part of the transport sector is freight transport. Freight refers to goods, commodities, or cargo transported from one place to another, typically in large quantities. Freight can include various items, from raw materials to manufactured goods. Freight transport allows us to move goods across borders, accommodating trade between parties and countries. Therefore, freight transport is crucial in the global economy and society. Globalization has increased freight worldwide and has created an incentive to transport goods as quickly as possible. Therefore, the efficiency in terms of time is enormously improved. Ordered goods can be expected to be delivered, with the origin on the other side of the world, within days for the lowest price, unfortunately, at a considerable cost to the environment.

Sustainability within freight transport is behind due to the high investment costs in the infrastructure and vehicles. In freight transport, three types of modes can be distinguished road, rail and air. Besides these modes, it is also possible to transship intermodally, meaning that multiple modes transport the freight. Road transport constitutes the highest proportion of overall transport emissions, in 2020 road transport emitted 77% of all European transport GHGs [19]. Due to the heavier weight and longer distances of heavy-duty trucks (HDT) compared to other road vehicles, HDTs are responsible for a relatively high proportion of GHG emissions. Within the overall road transport, HDT accounts for a quarter of the GHG emissions [24]. In 2015, HDT produced about 600 Mt of global CO_2 emissions [36].

In conclusion, the transport sector, particularly freight transport, significantly contributes to greenhouse gas emissions, primarily through the extensive use of fossil fuels. Road freight transport, with HDTs, contributes to these emissions. This emphasizes the need for sustainable solutions and innovations in green freight transport to mitigate environmental impact.

1.2. Green road freight transport

Regulations regarding emissions for HDT are expected to be an essential force motivating the transition of HDTs to a greener and more sustainable freight transport sector [36]. Compared to waterway and air transport, on a technical level, the alternatives for fossil fuels are accessible in road transport. Therefore, this research focuses on the three main alternatives for fossil fuels in road freight transport: battery electric trucks (BETs), hydrogen trucks, and bio-liquefied natural gas (Bio-LNG) trucks. The European Alternative Fuels Observatory (EAFO) mentioned these alternatives as the most promising for European road freight [14]. The EAFO also mentioned biocompressed natural gas (CNG) as a potential. However, CNG is not attractive for long-distance transport, mainly because of the limited energy storage volume [45]. Therefore, this CNG is not considered an alternative within this research.

BETs, Hydrogen trucks, and Bio-LNG trucks have their technical characteristics, each with corresponding advantages and limitations. Due to technical limitations such as drive range and the mismatch in supply and demand of these alternatives, it seems unrealistic to switch to just one of these alternatives in the near future. The electricity grid is already overloaded; most currently produced hydrogen is grey, and Bio-LNG is limited available. Therefore, a combination of these alternatives will be more realistic. In addition, combining alternatives can help overcome the alternatives' limitations [43].

BETs are vehicles powered by one or more electric motors, using energy stored in batteries. These trucks are charged by plugging them into an electrical charging station. BETs have a relatively high energy efficiency compared to the other alternatives. However, the major limitation is the limited drive range. The HD truck has to stop frequently to charge the battery; therefore, the overall transport time increases. Moreover, the charging time is relatively long compared to the other alternatives. Reducing this charging time has a negative effect on the battery lifetime and, therefore, on the environment. In addition, the batteries of heavy-duty trucks are heavy. Therefore, this affects the truck's payload capacity negatively [8].

Hydrogen vehicles use hydrogen fuel cells to generate electricity to power an electric motor. The fuel cell generates electricity by combining hydrogen with oxygen from the air, with the only byproduct being water. Hydrogen itself is not an energy source; it is an energy carrier. Currently, the infrastructure for hydrogen vehicles is limited. Therefore, heavy infrastructure development is required. The lack of infrastructure has resulted in high fuel and vehicle capital costs [8]. In addition, hydrogen and the purchase of trucks are currently relatively expensive.

Finally, Bio-LNG vehicles run on liquefied natural gas (LNG) produced from organic waste, such as food scraps, agricultural residues, or wastewater. Bio-LNG is considered well-suited for long-distance travel but also requires expensive liquefaction and handling infrastructure [4]. The overall emissions of Bio-LNG are very low. The plants used to produce biomass for Bio-LNG absorb CO2 as they grow, and when they are harvested and processed into Bio-LNG, this absorbed CO2 is released. This keeps the carbon in the atmosphere in a relatively short time frame, making it considered carbon neutral. Although the emissions are very low, other environmental effects are associated with using Bio-LNG as an alternative fuel for fossil fuels, including land use and water consumption.

1.3. Research Question and Objective

As a result of the high costs that are associated with the alternative technologies, the transition towards low-carbon and zero-emission technologies has been slower than expected. Freight transport operates on narrow margins, and companies are hesitant to invest in new technologies without proof of return on investment due to the high sunk cost of infrastructural projects. In addition, new technologies still have technical limitations regarding range and payload capacity. Therefore, research is needed to understand better the alternatives and the network needed if we combine different alternatives. Furthermore, improving the understanding will help to speed up the transition towards a sustainable transport sector.

This thesis sets out to address a research gap, which is further discussed in chapter 4. The research gap results in the following research question: *”How does combining Electric, Hydrogen, and Bio-LNG heavy-duty vehicles in road freight transport impact the costs and emissions in Europe while ensuring the reliability of the refuelling network, considering technological development, freight growth and limited supply?”* Cost in this thesis refers to financial costs and time costs. A Well to Wheel approach determines the system’s CO_2 emissions.

This research aims to explore how varying combinations of alternative fuels impact the system. A further understanding of the system behaviour will contribute to the ongoing transition towards sustainable freight transport. This is a complex challenge with many inter-dependencies between stakeholders and parts of the subsystems. The complex stakeholder landscape, which represents private and public interest, requires an understanding of the technical, economic and social factors to make the transition feasible. Therefore, all key elements of the Complex Systems Engineering and Management master’s program are relevant to this research field.

A two-pronged approach is used in this research to model long-distance freight transportation and optimize refuelling station locations across Europe. In this research, first, freight movements are simulated using freight modelling to assess traffic flows and demands. Then, the K-means clustering algorithm is used to place refuelling stations efficiently. The combination of freight simulation and location optimization allows exploring the alternatives’ impact on costs and the European environment.

2

Research Scope

Freight transportation is a complex system which is affected by several factors. To achieve the research objective and improve the understanding of the system, it is important to consider which elements should be included or excluded in this research. A model is a simplification of the real world. This section will dive deeper into the scope of the research and discuss which elements are included in the research scope.

This chapter highlights the following items for the research scope:

- Geographical
- Time
- Transport mode
- Technology
- Cost
- Emissions

2.1. Geographical

Freight is transported from A to B, within cities, countries and even continents. Therefore, the first choice in the scope is made geographical. Countries' borders or continents naturally set geographical boundaries. Since this study focuses on transportation by road, intercontinental freight is considered less relevant, as intercontinental transport is commonly carried out by ship or aircraft. On the other hand, freight transport is often transported internationally. Therefore, considering just one country would be insufficient to understand the system's behaviour.

Therefore, the focus of this study is the European road network. Europe is chosen because of two reasons. First of all, the availability of data. Secondly, thanks to the European Union (EU), free trade is possible between member states, and goods can easily be transported across land borders. This ensures that transporting goods between EU member states is relatively inexpensive. In addition, because of free trade between member states, there is little to no cross-border delay. As a result, it is modelled as a large distribution area with a mix of short and longer distances. Thus, various strengths and weaknesses of technologies can be expressed.

This interconnected infrastructure's core is the Trans-European Transport Network (TEN-T), which comprises linked national networks, including highways and railways. The primary objective of TEN-T is to establish a robust and well-connected network, ensuring efficient transportation of goods among EU member states [65]. The well-connected network, free trade between member states, and data availability make the European freight network a suitable network to study.

Considering the whole European Union as the scope for the research ensures a more comprehensive understanding of the system. However, it also creates complexity. Fostering changes on an international level requires better collaboration between the 27 member states of the European Union. In addition, the economic development varies per member state. Economic development correlates with the use of renewable energy sources [42]. Economically weaker countries invest less in renewable energy than economically more developed countries. Therefore, the development of the infrastructure of alternatives for fossil fuels can vary per member state. However, due to the time restrictions, the variation in the development of the alternatives is considered out of scope.

2.2. Time

There is also a delineation in time. The system will be considered for one year. This means that costs and emissions will be determined by year, and one-time investments will be transformed into annual costs.

Time within the system also has value. Value of time (VOT) is used for this purpose. The VOT will discussed later more in detail. It is assumed that every truck drives at the same speed regardless of which alternative is used. Therefore, the duration of trips is not considered since the alternatives have no difference in the duration of the trip. However, there is a difference between the range of an alternative and how long it takes to refuel. Therefore, the refuelling time of the alternatives is included as a penalty in monetary terms in the system.

2.3. Transport mode

As described in the introduction, freight is transported by various modes of transportation: rail, road, or air. This research focused only on the road because the emissions caused by road transport are the highest proportion of all three modes within Europe. In addition, the alternatives considered in this study only apply to road transport.

Trucks are divided into light-duty, medium-duty, and heavy-duty classifications depending on their weight. Heavy-duty trucks (HDT) are trucks designed with powerful engines and the capacity to transport large quantities of goods. HDTs are used to transport heavy or bulky cargo. HDTs have a gross vehicle weight of 15.000 kg or more. As described in the introduction, making passenger transportation more sustainable has already taken steps in the right direction. Nowadays, an increasing number of people in Europe are driving EVs. However, mainly due to the weight and payload of an HDT, it is more complicated to electrify them, and other alternatives might be more suitable. Furthermore, the overall emissions are high for HDTs due to the high use of fossil fuels. Because of the unique technical and social complexity of making HDTs more sustainable, this type of vehicle is included in this study.

2.4. Fossil fuel alternatives for road transport

There are several alternatives to fossil fuels in freight transportation. As mentioned in the introduction, chapter 1, this study considers three: Battery Electric Trucks (BET), Hydrogen Trucks and Bio-LNG trucks. The choice for these alternatives is based on the European Commission's (EC) plans. The EC aims to encourage the roll-out of these alternatives. The European Alternative Fuels Observatory (EAFO), part of the EC, highlights the potential of these alternatives within road freight transport [14]. In addition to electric, hydrogen and bio-LNG, CNG is also highlighted by EAFO as an alternative to fossil fuels. However, CNG is only seen as a good alternative for urban freight transport. As a result, CNG is seen as a less suitable alternative within this study and, therefore, falls outside the scope. In the literature review, chapter 4, each alternative will be discussed in more detail, and the potential strengths and weaknesses of each alternative will be further elaborated.

2.5. Supply Chain of Refueling stations

Figure 2.1 shows a simplified system representation. At the bottom of the figure, the freight trip between an origin and destination takes place. On the network, between origin and destination, there may be a refuel station where the truck can refuel or recharge. So, another subsystem within the system to consider is the refuelling stations. To dive deeper into the refuelling station, the supply chain of the refuelling station is considered briefly. This supply chain is the rationale for what costs and emissions are included in the system. The supply chain differs for each of the alternatives. However, in all

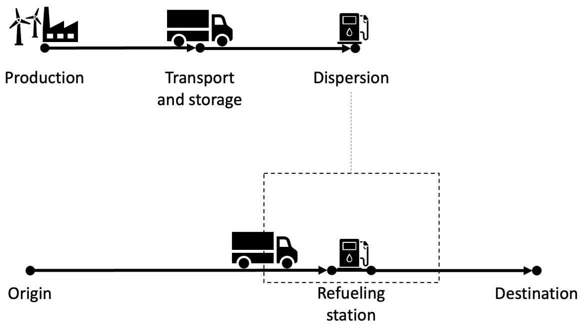

Figure 2.1: System Visualisation

three alternatives, the following steps can be distinguished: Production, Transport and Storage, and Dispersion, see figure 2.1.

First of all, the production. Electricity production for charging BETs can be done by renewable resources, like wind and solar, or by non-renewable resources, like coal and gas. Depending on how electricity is produced, cost and emissions are associated with it. The production of hydrogen, which is an energy carrier, is done by an electrolyser. It breaks the water molecules in Hydrogen (H_2) and Oxygen (O_2) molecules; in doing so, the electrolyser uses energy. If the energy used is from renewable resources, the hydrogen is called green. Bio-LNG is produced by using all kinds of waste products, for example, organic household waste, manure, or sludge from water treatment plants. From this waste, gas is produced. After this stage, it is in a gas state, so it should be liquefied. The production of the alternatives is more complicated than just described. However, for the purposes of understanding the system, the rest of these processes are not within the scope of the study.

After the production, the electricity or fuel should be transported from the production area to the refuel station. In this research, we assume that the electricity needed for the charging stations for BETs is transported over the European electricity grid. Therefore, it needs a connection with the grid. The energy transition requires more space in the electricity grid, but the grid expansion can not keep up with the rapidly increasing demand for grid space. Therefore, grid expansion is needed in order to accommodate the transition towards BETs. In addition, hydrogen and bio-LNG should also be transported from the plants to the refuelling stations. This can be done by truck or pipeline, for this research is chosen to focus on delivering hydrogen and Bio-LNG by truck. Therefore, pipelines and any already existing pipelines are out of scope.

Lastly, there are operations that are associated with the dispersion of the fuel at the station itself. For electric charging stations, this involves providing the necessary infrastructure for BETs to connect and recharge their batteries. The recharge time of BETs is long, so using fast chargers is the only approach to make BETs somewhat attractive. Therefore, only fast chargers are included in this study. For hydrogen refuelling stations, the process involves compressing and dispensing hydrogen gas into fuel cell vehicles. Conventional LNG trucks can run on Bio-LNG without any additions. Therefore, the trucks can use the same infrastructure as conventional LNG trucks. However, the use of conventional LNG is undesirable due to its environmental impact.

2.5.1. Costs

Costs are commonly used as one of the main metrics to measure the performance of various systems. This also includes transportation systems. All types of costs can be associated with the transport sector, depending on which perspective the system is viewed from. The next chapter, chapter 3, includes a stakeholder analysis and will describe the role of the European Commission (EC) as problem owner. For the EC it is important to look at the entire system's performance, to further analyse how to shape policies. Therefore, the overall system costs are taken into account as a metric.

Creating an infrastructure, like a refuelling station network, requires investment. These investments or expenses are often high and one-time, such as building a refuelling station or buying a truck. These expenses last for several years. Considering only the year of vehicle purchase or station construction gives a distorted picture, but likewise, not including these expenses at all gives a distorted picture. Therefore, the choice is made to spread these ”one-time” expenses over the average life of the product. These one-time expenses will be, therefore, transformed into annual costs. This applies to the cost of building the stations and purchasing a vehicle. Transport companies invest in vehicles. The cost of the purchase of trucks differs per alternative.

Furthermore, for the cost, it is relevant to consider the supply chain. First, the production costs. These are all costs that are associated with the production of the fuel. These costs vary per alternative. The transport cost depends on how the fuel is transported and the location of the plant and station. As mentioned before, the model assumes that the electricity grid will transport electricity, and hydrogen and Bio-LNG by truck. The dispersion cost includes investment cost, maintenance and operational costs for the station.

As previously mentioned, to include an important feature of alternatives, in addition to financial costs, time costs are included. It is also possible to express environmental impact in monetary terms. However, in this study, financial costs and environmental impact are used as separate metrics. Separating environmental impact from monetary terms allows for a more focused analysis of the ecological benefits or drawbacks of the alternatives. Measuring environmental impact in monetary terms can sometimes oversimplify or obscure the true ecological consequences. This research is primarily focused on the environmental and economic aspects of alternative fuels in road freight transport considering technical aspects of the alternatives. Therefore, other social costs, expressed in monetary terms, are considered out of scope.

2.5.2. Emissions

Besides cost, the yearly emissions are used as a metric for this system. As stated in the introduction, GHG involves multiple gas emissions. However, for this research, CO_2 emissions are considered. CO_2 is a commonly used metric to determine the total environmental impact and climate change of systems. CO2 is one of the most prevalent greenhouse gases emitted through human activities, notably burning fossil fuels like coal, oil, and natural gas. It represents a significant portion of total greenhouse gas emissions, a major contributor to climate change.

Particulate matter (PM) is not included in this research. PM impacts air quality and, therefore, can hurt public health. However, this research doesn’t include particulate matter in the scope. The research aims to focus on climate change and global warming. In this context, PM, which primarily affects local air quality rather than global climate, is out of scope.

Often, vehicle emissions are considered only in terms of what comes out of the tailpipe of the vehicle. However, this gives an incomplete picture, so a Well to Wheel (WtW) analysis is used in this study. A WtW analysis not only considers vehicle emissions but also gives a more complete picture of the environmental impact. A WtW analysis can be divided into Well to Tank (WtT) analysis and in Tank to Wheel (TtW) analysis. Whereas the WtT takes into account the production and distribution of the energy carrier. Furthermore, the TtW encompasses the use of the energy carrier by the vehicle itself. Alternative for fossil fuels, such as electric vehicles, don’t have tailpipe emissions. Therefore, these vehicles are typically associated with no environmental impact. However, the production of the energy needed for these trucks is often associated with environmental impact. The level of CO_2 emissions depends on how the energy is produced. Electricity and hydrogen is currently not fully produced by renewable energy sources. Therefore, the WtW analysis considers the total emissions of alternatives and is a reliable method to analyse the environmental impact of the alternatives.

Despite the fact that a WtW analysis provides a relatively comprehensive approach for analysing the environmental impacts, not all environmental impacts are taken into consideration. The WtW analysis generally does not account for the energy and environmental costs associated with the manufacturing, maintenance, and disposal of vehicles. This includes the extraction and processing of raw materials for vehicle production, manufacturing processes, and recycling or disposal at the end of the vehicle’s life. In addition, the energy and environmental impacts of developing and maintaining the necessary infrastructure for fuel production, distribution, and vehicle operation (such as roads, charging stations, and fuel stations) are out of the scope of a WtW analysis.

Decisions about the scope of the study were explained in this chapter. An overview of the most im-

Table 2.1: Assumptions

	Assumption
Geographical	Europe
Time	Yearly
Transport mode	Long distance HDT road transport
Alternatives	BET Hydrogen Bio-LNG
Electricity transport	Grid
Hydrogen transport	Truck
Bio-LNG transport	Truck
System Costs	Financial cost (production cost, transport cost, dispersion cost) Time cost (using VOT)
System emissions	WtW emissions

portant assumptions is provided in table 2.1. This research focuses on the European freight network transported by road. Where costs and emissions apply as a metric for the system and are determined per year. For emissions, the WtW emissions are used to consider the emissions released during the production of the alternative. The next chapter will provide a literature review, comparing and outlining the current literature on these alternatives. In addition, this chapter will identify, based on the knowledge gap, the research questions of this thesis.

3

Stakeholder analysis

Stakeholders have a crucial role within this system. Transportation infrastructure plays a pivotal role in our society, bringing together both public and private interests. Public interest encompasses the need for a safe, reliable, and accessible transportation system. The private interest is related to the efficiency for profit for individuals or businesses. The stakeholders within the system have different levels of power and interest. Analyzing the power and interest of the stakeholders is essential to have a full understanding of the system. In appendix A.1 the stakeholder analysis can be found. Based on this analysis, three key stakeholders are identified:

European Commission (EC) – Problem Owner: The EC helps to shape the European Union's (EU) overall strategy. The Commission manages the EU budget and proposes new EU laws and policies. In addition, the EC is also responsible for the implementation of the laws and policies [18]. Due to these features, the EC has the tools to make changes to the current state of the system. Therefore, The Commission can be seen as the problem owner of this system. Nonetheless, the EC has the ability to propose EU laws and policies, The Commission must take into account the 26 member states of the European Union. Creating policy or laws at a European level takes a lot of time, and should be well-founded.

Emissions aren't limited to country borders. The European Commission has set the following objective: by 2050, transport emissions will have to be reduced by 90%, compared to the levels of 1990. The roll-out of a sufficiently dense, widespread network of alternative fuels infrastructure is a critical element of this overall transition to low- and zero-emission alternative fuels [14]. This objective results in a high interest of this stakeholder. In addition, by creating policies and laws, the power of the EC can be considered as high.

Part of the EC is the European Alternative Fuel Observatory (EAFO). They are a technology-neutral organization and are there to be the bridge between the industry and the EC or local governments. They provide information and relevant data for the different parties. As they are a technology-neutral organization, they don't prefer one of the alternatives over the other. In appendix A.1 a summary of an interview with the EAFO can be found.

Oil and gas producers - Infrastructure owners: The transition towards renewable fuels has a huge impact on the current production of fuels and the infrastructure that is associated with this. Therefore, the parties in this industry have a high interest. Oil and gas producers within the system are not only responsible for the production of diesel or any of the alternatives but also own the fueling stations. Therefore, for realizing a charging/refueling infrastructure, the oil and gas producers are crucial to consider.

A feasible system requires investments in the production and infrastructure of the different alternatives. Oil and gas producers are increasingly concerned with the production of alternatives in addition to fossil fuels. In this way, the oil and gas companies are trying to achieve targets and improve their image. Investing in infrastructure is associated with high sunk costs. Oil and gas companies are profit-driven. Therefore, investing is a risk for these companies and can affect the profit margin. Hence, oil and gas companies don't have an initial incentive to make an investment in one of these alternatives. Especially not as long as there is not a huge demand for a specific alternative. Therefore, these companies need incentives to start creating an infrastructure. Thus, legislation from the European Commission is needed, including consequences if oil and gas companies fail in their actions.

Without an infrastructure for these alternatives, driving electric, hydrogen, or Bio-LNG is impossible. The power of the oil and gas companies is therefore high. Oil and gas producers do have a high interest and high power and are therefore considered as key stakeholders.

Transport companies - Fleet owners: The last key stakeholders in this system are the transport companies. Transport companies, often referred to as fleet owners, play a prominent role in the overall system. These companies are responsible for managing a variety of vehicles, particularly HDTs. The transport companies ensure the smooth transportation of goods from the origin to the final destination.

Transport companies, as key stakeholders, have a considerable influence on the system. The transition from traditional diesel-powered trucks to more sustainable alternatives largely depends on their decisions. However, there is a notable lack of motivation for such a shift. The hesitancy stems from the financial investment required to upgrade the existing fleet for sustainable alternatives. Additionally, the current absence of a well-established refuelling station infrastructure further complicates the situation. Making it challenging for transport companies to consider transitioning to alternative fuels.

Decisions made by the European Commission greatly impact international road transport. These decisions can affect road transport operations' efficiency, safety, and sustainability. Therefore, these decisions also have an impact on the transport companies. Thus, the interest of transport companies in the system is high, just like the power of this stakeholder. Hence, transport companies can be seen as key stakeholders in this system.

From the stakeholder analysis can be concluded that the EC is the problem owner, since it has a high power and interest in the system, besides that it also has tools to influence the system. The EC has, by regulation, providing subsidies or fines, the power to shape the system. Even though the EC can be considered as the problem owner, the EC doesn't have the power and the tools to fully influence the system since the system is partly public and partly privately owned. Therefore, collaboration and alignment between all the stakeholders are important to achieve the improvement of sustainability within the transport sector. Completely suppressing market forces and forcing them in certain directions may cause them to lose support among certain stakeholders. This can lead to resistance and subsequent failure of the ultimate goal.

3.1. System requirements

The stakeholders, as described in 3 have values that result in requirements for the system. Based on the values of the key stakeholders, in appendix A.2, the following value-based mission statement for the system is identified: "*Create cost-effectiveness, reliable and sustainable road freight system in Europe*". The mission statement includes three values of stakeholders that can be considered as important for the system:

1. **Cost-effectiveness:** To create a feasible refuelling network, the network should be cost-effective. For all three stakeholders, this is a very relevant value. However, cost-effectiveness does not have the same meaning for each stakeholder. For the EC, the European road network must be accessible to everybody to stimulate trade and the economic health of the EU. Affordability is a key component in this regard. In addition, for an alternative to penetrate the market, it should be cost-effective. For the transport and the oil and gas companies, this is important to achieve profitability. Currently, as mentioned in the literature review, chapter 4, cost-effectiveness is one of the main reasons that road freight transport is lagging behind due to the high investment and operational costs.
2. **Reliability:** Reliability is important for the EC because it helps increase trade between different

Table 3.1: System requirements

ID	Requirement	Description
1.1	Limit the number of refuel stations	To limit cost, the number of refuel stations should be limited.
1.2	Limit the total expenses of the road freight network	Limit the total system cost per year increase system profitability.
2.1	Ensure enough supply of fuels	To make sure all freight can be transported and the network is reliable, there should be enough supply of fuels.
2.2	Ensure meeting road freight demand	The ultimate goal of freight transportation is to move goods from A to B; sustainability should not come at that expense.
3.1	Limit the total GHG emissions	In order to achieve a sustainable road freight network, the total emissions of the system should be limited.
3.2	Ensure a long life span for the road freight network	A long life span of the road freight network is another aspect of sustainability that should be guaranteed.
3.3	Ensure national acceptance for the road freight network	Although country borders do not limit European transportation, its regulation affects countries individually. Therefore, a successful system also requires national acceptance.

regions, strengthening Europe's international trade position and economic development. For transport companies, reliability is also crucial. Insufficient fuel availability can cause significant delays. This situation can result in the loss of customers, or the transport companies receive fines if they can not deliver goods on time. The same holds for fuel stations; There must be an adequate fuel supply to supply stations. Otherwise, they may risk losing customers or harming their reputation.

3. **Sustainability:** Sustainability is a value for all three stakeholders. Sustainability is a broad concept. Sustainability refers to the ability to maintain or support something over the long term without causing significant negative impacts on the environment, society, or economy. Hence, sustainability is essential in terms of the environment and the project's lifespan. In the long term, it is beneficial to make a slightly higher investment now that lasts longer than reinvest in a new network every two years. Despite all three key stakeholders having sustainability as a value, it does not lead to the same actions among the three stakeholders.

The stakeholders' values result in system requirements, and the analysis can be found in appendix A.2. The analysis has shown that the road freight system should meet a set of requirements for a successful design for all key stakeholders. The system requirements and a short description are in table 3.1. The following section will reflect the current state of the system on the system requirements. Later in this study, these requirements will also be used to validate the system design.

4

Literature Review

Road transport has a crucial role in our society and economy. The intricate web of interconnected networks, from urban highways to long-haul freight routes and freight corridors, facilitates the movement of people and goods. The complexity can be an obstacle to reaching clean and sustainable transport and limiting the consumption of fossil fuels. Due to the big contribution to GHG emissions, road transport is often researched within the literature. This chapter provides a review of the current literature about sustainable alternatives in road transport. In the discussion of this chapter, the knowledge gap in the research field is discussed. The knowledge gap results in the main research question of this thesis. To support the main research question sub-questions are identified.

Research in the transport sector has had a big focus on passenger transport. Which often included research on passenger vehicles or mode choice behaviour. Research on freight transport has a growing interest in the literature. Within freight transport two types of freight transport can be distinguished: urban road transport and long-distance road transport. The main difference between these two is the distance and weight of the freight. Long-distance freight is transported over long distances often in HDTs. Urban transport is mostly in smaller vehicles and transported over smaller distances, within a city or small region. The urban freight transport has already made some steps in becoming more sustainable. Transport companies made investments in smaller electric vehicles for urban areas. Research has shown that in terms of trip patterns and daily mileage, small BETs are suitable for urban freight transport and city logistics. Furthermore, the deployment of small BETs could reduce exhaust and noise emissions [34]. However, long-distance heavy-duty transport has different characteristics. Therefore, electrification of the fleet is not so obvious and entails other requirements.

4.1. Opportunities and Challenges

Diesel-powered HDT has been the dominant technology in long-distance freight transport for the past decades. Diesel trucks have advantages over all sustainable alternatives: the extensive drive range and the relatively cheap vehicle and fuel costs. The market adoption of alternative fuels for HDT involves opportunities and challenges. The research of Anderhofstadt and Spinler [3] found that a truck's reliability, an available fueling/charging infrastructure and future fuel costs are the key factors for purchasing and operating an alternative fuel-powered HDT. In addition, the possibility of entering low-emission zones is currently the primary motivation to use alternative fuels. The article of Steenberghen and López [63] makes an additional notion, for overcoming barriers in the adoption of alternative fuels, the commitment of the industry is crucial. This commitment is commonly influenced by the performance of the technology and the environmental benefits.

Shifting from diesel powered trucks to sustainable alternatives requires investments, one of the main reasons that sustainability is lagging behind. The research of Giuliano et al. [21] suggests that alternatives are not yet economically competitive until about 2030. Therefore, solving the emission problems of HDTs may best be accomplished by flexible policies that support multiple new technologies. In addition, the article of Gómez Vilchez et al. [22] highlights, besides the importance of policy, the importance of improvements in transparency and reporting by countries, including vehicle estimates and infrastructure targets.

The research of Gustafsson et al. [24] has analysed and compared the GHG emissions of alternatives to the emissions of diesel-powered trucks. This research noticed that the GHG emissions of the alternatives highly depend on how the energy is produced. In 2021 the energy mix in Europe was about 22% renewable [50]. Based on the energy mix the research of Gustafsson et al. [24] research made an important notice: alternative fuels aren't necessarily more sustainable if the energy isn't produced by renewable energy sources.

BETs, Hydrogen trucks, and Bio-LNG trucks have advantages and disadvantages compared to the others. In the literature, researchers have compared the potential alternatives for fossil fuels in high frequencies.

4.1.1. Battery Electric Trucks

One of the alternatives that could have potential in road freight transport is BETs. EVs are getting a more prominent market position in passenger transport. Charging points for EVs are becoming more common, and private and public charging points are appearing. In terms of freight transport, BETs have not yet achieved this market penetration. BETs are promising alternatives for sustainable trucking and road transportation. Their substantial air quality improvements would, in turn, significantly improve environmental and human health nationwide [53]. According to the research of [53], these improvements depend on electricity generation. The advantages could be further improved by generating electricity from renewable energy sources.

Nevertheless, with the widespread market adoption of BETs in freight transport, the range anxiety and time of charging remains the biggest issue [5] [21]. According to the research of Bhardwaj and Mostofi [5], the success of BETs in the market depends on different aspects, including technical, business, customer, environmental and stakeholder aspects. A solution to overcome the technical limitations of BETs is mentioned by Bhardwaj and Mostofi [5]. By fast charging and battery swapping BETs could become more competitive. In addition, the research of Bhardwaj and Mostofi [5] queries the overall lifetime emissions of electric trucks or vehicles. Since the production of the batteries requires specific limited resources and causes emissions. Due to the limitations, compared to the other discussed alternatives, BETs are generally considered promising for shorter distances applications within freight transport. When the distances increase the drive range and charging time may pose greater challenges.

4.1.2. Hydrogen Trucks

The second alternative is hydrogen. Generally, there are three types of hydrogen: Grey hydrogen, Blue hydrogen, and green hydrogen. Grey hydrogen is produced from non-renewable sources of energy and emits greenhouse gases during its production. Currently, grey hydrogen is the most common type of hydrogen produced at this time. Blue hydrogen is produced in the same way as grey hydrogen, however, the carbon dioxide produced during the process is captured and stored. Therefore, blue hydrogen is considered as greener. Green hydrogen is produced through electrolysis, using renewable energy sources such as solar, wind or hydro-power to split water molecules into hydrogen and oxygen. Green hydrogen produces no greenhouse gas emissions during its production [2]. Currently, only 2% of the total hydrogen production is green hydrogen [17].

Li et al. [36] highlights the potential and challenges of hydrogen for freight road transport. Hydrogen trucks do have unique advantages: nearly zero emissions, short refuelling time, long driving range, high power, and good vehicle performance [36]. The extended drive range of these vehicles is considered a benefit over BETs. However, this article also mentioned many factors that affect the adoption of hydrogen HDT negatively, such as cost, operational considerations and political issues. Nonetheless, like other types of infrastructures, hydrogen could benefit from economies of scale. Consequently, hydrogen may expect huge cost reductions in the upcoming years, when the alternative is more widely used. The cost of HFCs in HDTs must be significantly reduced to meet the requirements for commercialization. This is in line with the article of Wanniarachchi et al. [70], which states that the lack of infrastructure is a major challenge for the global implementation of hydrogen fuel cell vehicles and cause high costs.

Table 4.1: Advantages and disadvantages of alternatives

Technology	Advantage	Disadvantage
BET	Environmental	Short driver range Payload Long charging time
Hydro	Short refueling time Zero emissios (in case of green hydrogen)	Grey hydrogen Expensive Required infrastructure
Bio-LNG	Zero emissions (WtW) Can use the LNG infrastructure	Limited availability

The article of Albatayneh et al. [2] notes that the success of hydrogen relies on several criteria, such as cost, efficiency, scalability, and environmental implications. In addition, the construction of hydrogen-powered vehicles is challenging and costly. The article compares hydrogen trucks with BETs, and it notes that the development of a complete hydrogen production, transportation, storage, and distribution system is more challenging than the more conventional fast-charging stations for BETs.

4.1.3. Bio-LNG Trucks

Bio-LNG has significant potential as a sustainable alternative for HDT due to its environmental and economic implications. In research of [66], a Well to Wheel (WtW) has shown that the emissions, especially in the Well to Thank (WtT), are 10 times lower for bio-LNG than for fossil fuels. This decrease in emissions is primarily attributed to the prevention of emissions that would otherwise arise from handling agricultural by-products.

According to Osorio-Tejada, Llera-Sastresa, and Scarpellini [46] the availability of Bio-LNG might be one of the biggest issues. Therefore, the EU recommended using LNG until Bio-LNG are commercially available on a large scale. The same study found that using conventional LNG can significantly reduce the environmental and human health impacts of heavy-duty transport. According to Osorio-Tejada, Llera, and Scarpellini [45], LNG for road freight transport is a potential alternative to replace traditional fuels in the short to medium term. This aligns with other research that considers LNG as a transitional option towards a fully decarbonised transport sector [48].

Besides the environmental benefits of Bio-LNG, this fuel has another advantage. The infrastructure required for Bio-LNG is similar to that of conventional LNG. The refuelling stations needed for these alternatives should meet the same requirements as conventional LNG refuelling stations. However, the research of Prussi et al. [49] highlights the need for a policy perspective related to the refuelling infrastructure and production of Bio-LNG. To prevent the infrastructure from becoming a barrier to the development of Bio-LNG,

The advantages and limitations of the alternatives are summarized in table 4.1. In addition to the advantages and disadvantages of these alternatives, future developments play a role in realising a sustainable road freight network. This includes technological developments of the alternatives, growth of freight and the availability of the alternatives.

4.2. Discussion and knowledge gap

Table 4.2 compares the existing literature. Previous research has focused on comparing the alternatives of the road freight network. It highlights the potential of one alternative over the other based on technical and/or social aspects; however, the transition will not shift to one of the alternatives but will probably be a combination of the alternatives since, currently, investments are made for infrastructures. Regarding the author’s knowledge, no research has addressed this earlier. Therefore, a knowledge gap appears: combining alternatives and exploring the effects of the implementation of the alternatives on the costs and emissions of the network. This thesis research will fill this knowledge gap, combine the alternatives, compare the refuelling networks based on cost and emissions, and optimize the refuelling network. Therefore, the following research question is identified:

”How does combining Electric, Hydrogen, and Bio-LNG heavy-duty vehicles in road freight transport

Table 4.2: Articles included in literature review

Article	Diesel	BET	Hydrogen	Bio-LNG	Compare	Combine
Anderhofstadt and Spinler [3]		x	x	x		
Giuliano et al. [21]	x	x			x	
Gustafsson et al. [24]	x	x	x	x	x	
Steenberghen and López [63]		x	x	x	x	
Gómez Vilchez et al. [22]		x	x	x		
Sen, Ercan, and Tatari [53]		x				
Bhardwaj and Mostofi [5]		x				
Albatayneh et al. [2]		x	x		x	
Li et al. [36]	x		x			
Wanniarachchi et al. [70]			x			
Osorio-Tejada, Llera, and Scarpellini [45]				x		
Prussi and Chiaramonti [48]				x		
Osorio-Tejada, Llera-Sastresa, and Scarpellini [46]				x		
Tratzi et al. [66]				x		
Prussi et al. [49]				x		
Thesis	x	x	x	x	x	x

impact the costs and emissions in Europe while ensuring the reliability of the refuelling network, considering technological development, freight growth and limited supply?"

4.3. Research questions and structure

This section will address the sub-questions that will be used as support for answering the main research question. In addition, this section will discuss the further structure of this thesis and address how these sub-questions are related and presented in this thesis.

4.3.1. Research questions

The literature review provided insights into the current literature on this topic. In doing so, it has also provided insight into the knowledge gap within this research field. Based on the main research question, a series of sub-questions are formulated. These sub-questions help to answer the main research question.

RQ1 *What is the current state of Europe's road freight transport industry?* To change the system, it is important to understand the current system. Therefore, this research question focuses on the understanding of the system. This research question dives deeper into which key stakeholders affect the system and will analyse which requirements are relevant for this system.

RQ2 *What technical elements affect the refuelling network of heavy-duty vehicles?* Research question 2 dives deeper into the more technical factors of heavy-duty vehicles and the analysed alternatives. All alternatives have their technical advantages and limitations over the others. Therefore, these technical elements have an influence on the system and the performance of the alternatives. This research question determines the input variables of the model.

RQ3 *What is the effect of the alternatives individually on the network in terms of costs and emissions?* Research question 3 will be answered by creating and running the model. The model includes the elements defined in research questions 1 and 2. A variety of experiments are performed to get a better understanding of the effect of the alternatives on the network and to verify the model.

RQ4 *What are the future projections for the growth and technology of electric, hydrogen and bio-LNG* *vehicles in the road freight industry in Europe?* All of the alternatives are still in development. It is crucial to consider the best understanding of the future to provide a valuable answer to the main research question. Therefore, future projections for freight demand and the technological development of alternatives should be considered.

RQ5 *What is the effect of the projections on the road freight network in terms of cost and emissions?* By running the model for the future projections (scenarios), the model can determine which network ranges cause the lowest cost and emission combination.

RQ6 *What policies are required to realise the optimal road freight network?* This research question is a sequel to RQ5. Interventions are needed to achieve the network as determined by the model. Therefore, this research question will show the impact of different policy options on emissions and cost, which is used to substantiate the choice for one or multiple interventions of the problem owner.

4.3.2. Structure

The objective of this research is to improve the understanding of how different alternatives relate to each other and what the impact is on the cost and emissions of the system. This research unfolds through sub-questions, each addressed in dedicated chapters, contributing to exploring the subject matter.

Research question 1 will be answered in chapter 5. In it, a complete system description will be given, using the stakeholder analysis, system requirements and institutional analysis, to reflect the current state of the system.

After describing the current system, suitable methods are discussed in chapter 6. This method is thereafter used in chapter 7. In this chapter, the implementation of the model is specified. This includes analysing which technical elements affect the system. Therefore, this chapter answers research question 2.

Research question 3 follows from a set of experiments. The experimental setup and results can be found in chapter 9 and 10. A scenario analysis is performed to determine the future projections for economic growth and technological development; this can be found in chapter 9. This will answer research question 3. Next, experiments are conducted under different scenarios. This will make it possible to examine under which input parameters the model shows desired behaviour; this will answer research question 5. The results of the different scenarios will be discussed in chapter 10

Finally, chapter 12 examines how different policies can ensure that the system shows the desired behaviour. In the conclusion, the main question will be answered. The discussion will be a reflection on the research and the results. Furthermore, the discussion also includes a recommendation for further research.

5

System description

This chapter includes the system description. This chapter will build on the stakeholder analysis of chapter 3. The stakeholder analysis identified three key stakeholders: European Commission (EC) as problem owner, Oil and Gas producers, and Transport companies. This chapter will first reflect on the current system and the system requirements. Furthermore, an institutional analysis is performed to provide a complete overview of the system's institutions. The conclusion of this chapter answers research question 1: *What is the current state of Europe's road freight industry?*.

5.1. Reflection of current system on system requirements

By reflecting on the system requirements, the current state of the system can be discussed. This further specifies in more detail whether and in what areas interventions are needed within the system.

First of all, cost-effectiveness. This requirement is met. As the study by Giuliano et al. [21] states, alternatives to fossil fuels are not yet economically competitive with fossil fuels, at least until 2030. This situation leads to diesel remaining the most cost-effective and, therefore, the dominant fuel choice for road freight transportation. The industry's reliance on diesel is primarily driven by its cost advantages, as businesses in the competitive freight market often prioritize economic efficiency. Even if the price per unit of fuel goes down, there are still high costs to establish the infrastructure or purchase the vehicles.

Second, reliability. Currently, enough diesel is available for a reliable road freight network within Europe. However, in the future, this could become a problem if the use of non-renewable resources continues. In addition, the use of oil and gas may also be jeopardized by geopolitical issues, such as the conflict with Russia. The conflict with Russia significantly affects oil and gas supplies in the West. The current network for diesel ensures that the total freight demand can be met and goods can be moved from origin to destination. However, this might be a problem in the future and network reliability may be compromised. These insecurities in terms of availability may result in price fluctuations.

Last is sustainability. Sustainability refers to the life span of the road freight network. This system requirement is not achieved in the current system. The system's life span may be compromised because of the impact on the environment and the use of non-renewable resources. The requirement for limiting GHG emissions is not met. Available alternatives provide fewer emissions, so using diesel does not provide the fewest emissions in the system.

5.1.1. Cost versus Emissions

The EC generally seeks a balance between economic growth, environmental protection and social justice. Making a trade-off between costs and emissions for the EC depends on several factors, including the policy goal, societal priorities and long-term objectives. On the one hand, climate goals seem to be an essential reason for prioritizing emissions as a system performance indicator. However, the importance of a market should not be underestimated for the further development of the alternatives.

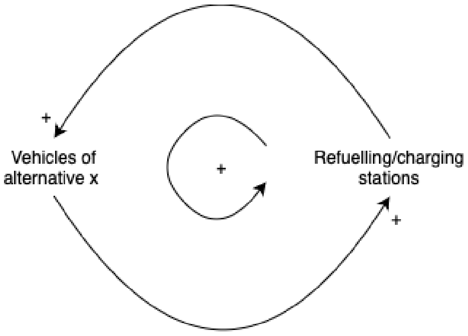

Figure 5.1: Chicken and egg problem

During an interview with the EAFO, which can be found in appendix A.1, it became apparent that it is a very political consideration, bringing together the interests of different sectors. As a result, it is impossible to give an unequivocal answer as to whether costs or emissions are more important in this system. Therefore, it's challenging to prioritize either cost or emissions in the system. This study aims to shed light on this intricate balance, suggesting an approach that initially focuses on controlling system costs and subsequently addressing emissions considerations. Such a strategy acknowledges the importance of maintaining a viable market and national network acceptance, ensuring that efforts towards cost-efficiency do not result in unacceptable emissions. The interplay between cost efficiency and emissions reduction remains pivotal in shaping a sustainable and economically viable European road freight system.

5.2. Institutions

Interactions between the key stakeholders are a balance between cooperation, negotiations, and competition. This section describes the institutions within the system. Institutions are rules and procedures that shape the interactions and relations between individuals or organisations.

To understand the complexity of the interactions between stakeholders and analyse the institutions, the Institutional Analysis and Development (IAD) framework of Elinor Ostrom [47] is used. The analysis in A.3 describes the interactions between the stakeholders and further elaborates on the governance structure of this system. This analysis highlights that the incentive for stakeholders to invest in a renewable refuel network is low due to the high investments and associated sunk cost, uncertainty, and currently low return. The framework helped to identify a chicken and egg problem within this infrastructure.

5.2.1. Chicken and egg problem

Creating a sustainable road freight sector can be considered as a chicken and egg problem. This kind of problem can occur in various contexts. Two factors require progress, but neither factor can move forward without the other. In the context of road freight, on the one hand, infrastructure is needed to make it feasible for transport companies to switch towards a more sustainable alternative vehicle. On the other hand, the refuel companies will not create a refuelling network as long as there is no demand for that fuel. Therefore, a positive feedback loop occurs; see figure 5.1.

This highlights the importance of policy on an international level. Policies can create an incentive to start the transition for one of the two sides of the chicken and egg problem. This research focuses on creating the infrastructure because, without it, it is not feasible for alternatives to become operational and bring goods from origin to destination. Also, research has highlighted the importance of developing the refuelling infrastructure [70], [49]. Therefore, this thesis assumes that when the infrastructure is developed, the market will be stimulated in the right direction. The stimulation of the infrastructure side of the market could be a solution for the chicken and egg problem. After a good refuelling or charging infrastructure is in place, one of the transport companies' concerns has been eliminated. Therefore, operating a vehicle that uses one of the alternatives is less risky. This reduces the barriers that exist for transportation companies to make the transition towards HDTs that run on alternatives for fossil fuels.

5.2.2. Ownership

Currently, the majority of the refuelling stations are privately owned and operated. These can range from large oil and gas corporations to smaller independent operators. By realizing a new infrastructure, such as a road freight transport network, ownership can be an issue. The government or EU wants to locate stations at specific locations to stimulate sustainable infrastructure development. However, the government doesn't own the station itself. Governments in Europe often play a role in shaping the ownership structure through policies and incentives. Financial support or regulatory measures may encourage private investment in refuelling infrastructure or promote the development of stations that support cleaner energy options. Given the scale and significance of a road freight network, governments at the European and national levels may collaborate with private companies to facilitate the network's development, ownership, and operation. The collaboration ensures the balance between public interests and private sector efficiency.

5.2.3. Current regulations

The EC has set regulations regarding using alternatives within road freight transport. In general, Europe has the European Climate law. It writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. The law aims to ensure that all EU policies contribute to this goal and that all sectors of the economy and society play their part. The Climate Law includes measures to keep track of progress and adjust our actions accordingly. Furthermore, the Law addresses the necessary steps to get the 2050 target [13].

Besides the European Climate Law, an agreement was reached between the European Parliament and the Council: The new Regulation for deploying alternative fuels infrastructure (AFIR). This is an ambitious new law agreed to deploy sufficient alternative fuel infrastructure. The AFIR has set mandatory deployment targets for the road sector's electric recharging and hydrogen refuelling infrastructure. By making a minimum of recharging and refuelling infrastructure available across the EU, the regulation will end consumer concerns about the difficulty of recharging or refuelling a vehicle [16]. The regulation includes recharging stations dedicated to HDTs and hydrogen refuelling infrastructure.

In addition to these regulations, there are also regulations regarding fuels. Bio-LNG is made from organic waste, like manure, food scraps or damaged crops, and is, therefore, a modern way of waste management. In 2024, under the Waste Framework Directive, EU countries must collect organic waste separately. This offers the opportunity to scale up the production of Bio-LNG [15]. Bio-LNG can't be made from resources that could also be considered food or can be used to produce food. Therefore, the supply of this alternative is limited.

5.3. Conclusion

This chapter has answered the research question: *What is the current state of Europe's road freight transport industry?* In conclusion, in the European road freight industry, 3 key stakeholders can distinguished: the EC, Oil and gas producers and transport companies. The first steps have been taken in the regulation and development of a more sustainable sector. However, oil and gas producers and transportation companies still lack investment incentives due to the chicken and egg problem. Therefore, it is important that the EC, in dialogue with other stakeholders, develops policies and regulations to stimulate the transition. To increase the success rate of the system and encourage alternatives, it is important that the system be cost-effective, reliable and sustainable. The current system doesn't ensure all of these requirements. The current road freight network meets the requirement only in terms of cost and reliability. However, in terms of sustainability, a lot of progress is required. It is a battle between short-term financial gain and longer-term sustainability of all three aspects of the system. Policymakers need to outline a longer-term vision that gives direction on where all policies should move the system in the medium term.

6

Method

Transport of goods over long distances facilitates the flow of raw materials, finished products and everything in between. This chapter discusses methods for long-distance freight modelling and refuelling station location optimization, laying the foundation for the model described in chapter 7. Based on the characteristics and limitations of the methods, the most suitable method is selected.

Figure 6.1 shows the sub-steps within this research. First of all, the simulation of freight. A better understanding of freight distribution within Europe is created by simulating the freight that moves over the network. The simulation is needed to assign freight to one of the alternatives based on the distance between the origin and destination of the trip or based on a percentage of distribution of the alternatives. This specifies the truck flow over the roads of Europe, which is an input for location optimization. After determining the truck flow, the location can be optimised. This results in a refuelling network with refuelling stations, including the cost and emissions of this network. 6.1 discusses the steps within freight modelling and highlights the applicability to this research. 6.2 discusses the methods for location optimization and selects the suitable method for this research.

6.1. Freight modeling

Freight modelling is a method of analysing by simulating the movement of goods and commodities from one location to another. Freight modelling aims to understand and predict how goods are transported, the routes they take, the mode of transportation and the associated costs and environmental impacts.

There can be a distinction between long and short-distance models in freight modelling. Within these models, there are aggregate and disaggregate models. Aggregate models, focusing on specific commodities and using time series data to estimate current demand to address large-scale problems. Disaggregate models include the simulation of the behaviour of several players involved in the decision process. In short, freight transport models assess the impact of different policy measures.

Four steps can be distinguished within freight transportation models [9]:

1. *Production and attraction:* Freight modelling often uses origin-destination (OD) matrices. OD matrices include all freight that moves between an origin and destination assigned to a particular transport mode. These matrices provide a structured representation of travel patterns and flows. The matrices include origins and destinations, trip volumes, and mode of travel.

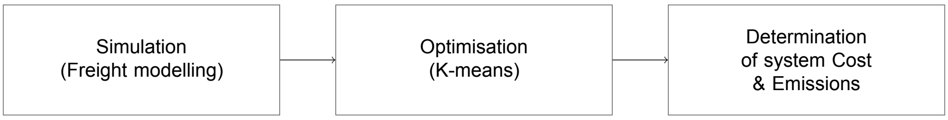

Figure 6.1: Method overview

2. *Distribution:* The next step in freight modelling is the distribution. Based on the OD matrix, it distributes the flow in goods transport between the origin and destination. In other words, the model uses the cells of the OD matrix to simulate the flow of goods.
3. *Modal split:* The allocation of the commodity flows to modes is determined. Within freight transport, there is a distinction between 4 types of modes: road, train, combined transport, and inland waterways.
4. *Assignment:* After converting the flows in tonnes to vehicle units, these can be assigned to networks.

By taking these steps, a freight simulation can be created, which shows the movement of goods over the network. By assigning the flow of goods between the origin and destinations to an edge of the road network. The simulation provides insights into which parts of the network are more congested. Furthermore, the freight model can determine the demand for a particular fuel based on the number of trips and distances.

6.2. Location optimizing

Besides the freight modelling for the simulation, location optimisation is part of this research. The optimisation is used to determine the optimal location for refuelling stations. The location of the refuelling stations affects the cost of the system. The location affects how easily fuel can be transported to the station. If a station is far from fuel supply points, such as refineries or ports, the transportation costs for the fuel will be higher, increasing the overall operational costs of the station. There are different ways of determining the optimal locations within a network. Within the location optimisation for refuelling stations, we can distinguish different methods. These methods and their fit with this research will be briefly discussed.

Flow Refueling Location Model (FRLM): The FRLM locates a given number of refuelling stations on a network to maximize the traffic flow among origin-destination pairs that can be refuelled given the driving range of alternative-fuel vehicles [35]. In other words, the FRLM maximize the number of trips intercepted. The model considers the interactions and dependencies between various regions or nodes in a transportation network.

P-median: The p-median model minimizes the total weighted distance travelled from each node to its closest facility. The total distance is minimized by optimizing the location of the refuelling stations and assigning them to demand points. The p-median model locates fuel stations near where people live. This model is mainly used for urban areas [33].

Agent-Based: Agent-based models can help to explore the emergence of complex behaviour. In agent-based models for location optimization, there are two types of agents: the driver and the station owner. After a given period, the driver updates his/her vehicle, and by doing this, it considers the utility of adopting an alternative. The station owner is considering building the refuelling station at a location where many vehicles are passing the location. This method makes it uncertain whether this algorithm can find a globally optimal solution [33].

K-means: K-means is a clustering algorithm. The optimal location is determined by minimizing the mean distance between the centroid and the other nodes. Therefore, the centroid of a cluster can be considered the optimal location for a refuelling station. The centroid is the point that minimizes the distance to all points in the cluster, making it an efficient location to serve all these points. This method is especially suitable for big data sets since it is easily scalable. The number of stations, or clusters, is an input for the algorithm. Therefore, the model doesn't provide this.

6.2.1. Fit with research

These methods have their corresponding strengths and weaknesses. By reflecting on the objective of the method and its characteristics, the most suitable method can be selected. A brief overview of the characteristics of each method is shown in table 6.1.

Most of the methods are primarily suited for analyzing urban freight transport. FRLM is not suited for this research due to the high mathematical complexity of this model. Agent-based modelling primarily helps to understand the behaviour resulting from interactions between agents. This research doesn't

Table 6.1: Comparing location optimization methods [33]

	Method Objective	Single/multi objective	Limitations
FRLM	Minimize travel distance and time for vehicles to refuel.	Single	The model doesn't consider driving range, station capacity, safety or prices.
P-median	Minimize total travel distance or time from demand points to refueling stations.	Single	Demand is not associated with the flow of traffic. Primarily used for analysing urban areas.
Agent-based	Understanding emergence of complex behaviour and interactions between agents	Multi	The results of the simulations depend on initial conditions which
K-means	Using clustering to minimize the mean distance between the centroid and the nodes assigned to the cluster.	Single	It doesn't determine the optimal number of stations.

focus on the understanding of interactions between agents. Therefore, the objective of this method doesn't match the objective of this research. P-median doesn't take into account the demand that is associated with the flow of traffic. As described in table 3.1, one of the system's requirements is to meet freight demand. By using the P-median method, meeting this requirement can't be ensured.

K-means is the most suitable method for this research based on its characteristics. First, the advantage of this method being scalable for an extensive data set is a huge advantage over the others in this context. This research focuses on Europe. Therefore, freight is moving from origin to destination. The distances can vary from short to very long, and crossing the whole of Europe. Due to the huge data set associated with these origins and destinations, scalability is an essential feature. Section 6.3 will elaborate further on this method and its applicability in this research.

6.3. K-means clustering

K-means is an algorithm that is used for various purposes. K-means is a clustering algorithm that tries to partition the data set into predefined distinct non-overlapping subgroups (clusters), and each data point belongs to only one cluster. The algorithm minimizes the mean of the distance between the nodes within the cluster [57]. A cluster assigns nodes to a refuelling station. The cluster's centroid is a station within the network because it is an efficient location to serve the demand points.

The road freight model consists of roads that, in the network, are transformed into edges between nodes. The roads/edges have a truck flow. K-means uses data points to determine the optimal locations for the centroids. An edge is not a data point. Therefore, the edge should be transformed into a data point for the model. These demand points represent the demand for an alternative fuel for a specific geographical location. The location of the demand point is the geographical centre between two nodes or the middle point of the edge. To assign the truck flow of the corresponding edge to the demand point, the number of trucks is divided by the length of the edge. This results in a demand point with a truck flow per kilometre.

The truck flow is the weight of the data point. These weighted data points are used in the weighted K-means. In standard K-means clustering, each point is considered equally. However, weighted K-means assign more weight to the more congested roads. This means that during the clustering process, roads with more truck traffic (higher fuel demand) will have a greater influence on the location of the cluster centres (refuelling stations). Therefore, in your model, more congested locations (roads with higher truck traffic) will naturally attract the cluster centres (refuelling stations) closer to them. This ensures that areas with higher fuel demand due to more truck traffic are more likely to have nearby refuelling stations.

The K-means algorithm as the method has advantages and limitations. One of the most significant advantages of the method is that it is relatively efficient and, therefore, scalable for an extensive data set. This study takes all trips during a year, which results in more than 1.5 million cases. So, scalability is an essential feature of great importance for this research.

A disadvantage of K-means is its sensitivity to the initial placement of centroids. Different initialization may lead to different solutions. Therefore, this method may conduct non-optimal results [57]. In addition, the major limitation of the K-mean algorithm is that it does not provide you with the optimal number of clusters; you have to define the number of clusters yourself. However, this limitation also brings opportunities; it allows the user to set the number of clusters in the most useful way for the user's preferences.

6.3.1. Number of clusters

As stated before, K-means clustering doesn't determine the optimal number of clusters. The number of clusters is an input for this algorithm. Therefore, the number of clusters should be pre-determined. The literature has different methods for determining the number of clusters, such as the Elbow method and the Silhouette Score.

Elbow Method: For Elbow Method, the K-means algorithm runs for a range of values of K. The sum of the squared distances is plotted. Thereafter, a trade-off should be made between complexity and accuracy. The location of the elbow, the nodal point of the graph, is considered the optimal amount of clusters.

Silhouette Score: The Silhouette Score measures how similar a data point is within a cluster compared to other clusters. In order to determine the number of clusters, the K-means algorithm runs for a range of K values. Thereafter, the average Silhouette score is determined per run. The K value with the highest Silhouette Score is the optimal number of clusters.

Chapter 5 outlines the importance of meeting the demand for an alternative fuel to create a reliable network. Therefore, a sufficient number of stations is needed in the network. The Elbow Method and the Silhouette Score can not ensure meeting the demand for an alternative fuel. Therefore, neither of these two methods is desirable for this study to determine the number of clusters. Siderius [56] defined another method to determine the optimal number of refuelling stations. The fuel demand can be met with enough stations, considering a station's average capacity. Therefore, the number of clusters for this research is determined by dividing the total yearly fuel demand by the yearly capacity per station. This would give the number of stations that is sufficient to meet the demand for the fuel.

However, determining the number of clusters using this method does not consider the geographic distribution of demand for the alternatives. The model uses the demand points as weighted data in the weighted K-means clustering to ensure a reliable network. This ensures that in areas with greater demand for alternative fuels, a proportionally greater number of fueling stations are allocated. This method, therefore, quantifies the number of stations needed and strategically allocates them according to regional demand variations. Thus, this approach attempts to include enough stations and strategically consider the geographic distribution.

7

Model Specification

This chapter specifies the model which is used for this thesis. For the model specification, the previous chapters are taken into consideration. The scope and system description highlight which elements are taken into account and where the boundaries of the model are. The method chapter, chapter 6, has discussed the two methods used within the model to simulate the freight that moves across Europe and optimise the location for refuelling stations based on demand points. This chapter provides a detailed specification of the model used for experiments to understand the system. Therefore, this chapter answers research question 2: *What technical elements affect the refuelling network of heavy-duty vehicles?*

First of all, a global specification is given. This generally identifies the steps within the model to determine the overall system costs and emissions. After that, this chapter will dive into the data used within the model. Finally, the steps described below will be discussed in more detail.

7.1. Steps within the model

The model is made in Python. Within the model, the following steps can be distinguished:

Read freight data: The model reads the data of the freight, nodes and edges from the data set. Further elaboration about the freight data can be found in 7.2.1

Create a graph: The model constructs a graph to analyze freight movement across Europe. This graph comprises two primary elements: 1) Nodes: These points on the graph represent the origin and/or destination locations of freight. 2) Edges: These are the lines connecting the nodes. Each edge represents a road or path the freight takes from one location to another within the network.

Furthermore, the model assigns a 'truck flow' to each edge. Truck flow is a measure of how much freight traffic passes along that road. If a road (edge) is used frequently, it will have a higher truck flow. Conversely, some roads might not have any freight traffic at all. In these cases, the truck flow is zero, but these roads are still included in the graph to represent the complete road network. The graph includes all roads, providing a comprehensive view of the road transportation infrastructure.

Determine values for the parameters and assign freight to an alternative: Based on the advantages and disadvantages of alternatives, as described in the literature review, chapter 4, certain alternatives can be expected to be cheaper to use at certain distances than others. Therefore, distance ranges are used. The data set includes origin and destination data, including the distance between the origin and destination. These distances can be divided into kilometre ranges. For example, from 0 - A km will be driven by alternative X_1, from A to B with alternative X_2, and from B to maximum distance with alternative X_3.

However, this approach is too rigid. Although policies can guide stakeholder behaviour, it is still impossible to prohibit specific trips from being driven with a particular alternative. Therefore, it splits the data by assuming that a certain percentage is driven by each of the alternatives within these ranges. To understand the model's behaviour and include the uncertainty of choice in alternatives, the model generates random values for each of the model parameters. The trips are assigned to one of the alternatives based on these criteria.

Create new data sets: Three new data sets are created: one for each of the alternatives based on which of the alternatives the model assigns the freight.

Check availability of alternatives: The model checks whether enough fuel is available based on the total kilometre driven by each alternative. If there isn't enough alternative, it generates new parameter values.

Determine the number of stations: To perform K-Means, the number of clusters should be determined. The number of stations is calculated based on the total demand for an alternative and the average capacity of the station. The model assumes equal capacity for each of the refuelling stations.

Create demand points: Based on the truck flow of each edge and the geographical locations, demand points are created. The demand point represents the demand for an alternative fuel based on the consumed energy by the truck. The geographical location of these demand points is the geographical centre between two nodes. In addition, these demand points have a truck flow per kilometre, which is determined by the edge's yearly truck flow divided by the edge's total length.

Determine the location of refuelling stations: By using the demand points and the number of stations as input for the weighted K-means, the optimal location of the stations per alternative is defined.

Supply the refuelling stations: The supply of refuelling stations is considered. The model determines the closest fuel plant and calculates each refuelling station's transport and storage cost.

Determine cost and emissions per alternative: Based on the outcomes, the cost and emissions can be calculated according to the calculations as explained in appendix B.

Determine total system cost and emissions: By summing up the cost and emissions per alternative, the total system cost and emissions are calculated according to 7.3.5 and 7.3.6.

7.2. Data

The model uses data to determine the cost and emissions of the system. This section will discuss the data used in the model. Furthermore, this chapter explains how the data is transformed to make it applicable to this research.

7.2.1. European Freight

The model uses European freight data of Speth et al. [59]. This data is based on the Nomenclature of Territorial Units for Statistics (NUTS) level 3. The NUTS classification system is a hierarchical system used by the EU for dividing countries into various territorial units to facilitate statistical and administrative purposes. NUTS-3 is the most detailed level of this classification and typically represents sub-regions or counties within a country. These maps are useful for various purposes, including statistical analysis, regional planning, and resource allocation, as they provide a finer-grained view of a country's or region's administrative divisions, allowing for more localized data analysis and decision-making.

The freight data of Speth et al. [59] includes four data sets:

1. *Truckflow freight:* The Truckflow freight data includes all freight that moves within Europe. The origin and destination, distance, truck flow, and the edges between the origin and destination are provided in this data. In addition, this data is based on data from 2010. Later it has been updated for 2019. Furthermore, this data contains a forecast for 2030 based on the growth rate from 2010-2019. This data set includes 1.514.613 cases, corresponding with 1.514.613 origin and destination combinations. Within the model, this data set is used for freight modelling.
2. *NUTS-3-Regions:* This data set includes all NUTS-3 regions, including the name and geometric centre of the region. This data isn't used for the model.

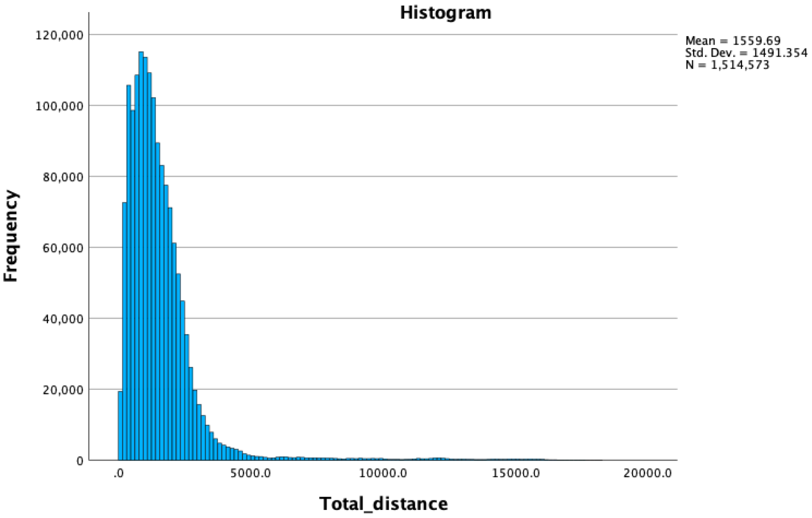

Figure 7.1: Freight data frequencies distances

3. *Network-nodes:* The Network-nodes data set includes data about the network nodes, including their geographical coordinates and the ETISplus-zone. The network has 17435 nodes. The geographical coordinates of this dataset are used to locate the nodes at their geographical location in the network.
4. *Network-edges:* The last data set involves data about the network's edges. It includes the two nodes between the edge and the expected truck flow for 2019 and 2030 of that edge. The edges represent roads of the European road network. The network has 18449 edges. This data is used to create edges within the model network.

Due to the size and complexity of the data set, it is important to understand the freight data further. Therefore, some descriptive analyses have been performed. Due to the size of the data set (1.514.613 cases), this is performed with SPSS. Figure 7.1 shows the frequencies of appearance of distances in the data set. From this figure, it can be concluded that the lower distances between origin and destinations appear more often in the data set. The distance between the origin and destination that occurs most often is 1271 kilometres. This number seems relatively high compared to the averages Eurostat provides [51]. This difference can be explained by the fact that the data set considers a larger area than just the 26 member states of the European Union; the UK, Russia and Turkey, for example, are also included in the data set. In addition, the longer distances do not frequently appear in the data set. 95% of the cases fall within the 3500 kilometres. More descriptive analysis can be found in appendix B.1, table B.1.

The rollout of infrastructure can take decades. Therefore, the model's results should also make sense for future freight forecasts. Future scenarios will be further elaborated in chapter 9. The data set of Speth et al. [59] only include a forecast of 2030 using a growth rate. The growth rate is used to determine freight demand for 2040 between an origin and destination combination; according to *Road freight market size Europe 2010-2025 | Statista* [51], the road freight is expected to increase further. The article form Speth et al. [59] had defined the growth rate as in equation 7.1. Thereafter, this growth rate is used in equation 7.2 to calculate the value for the truck flow in 2040 that goes to node i. This data transformation is performed with all cases of freight data to create a forecast for 2040. It is important to note that forecasting freight depends on many factors. So, the growth rate is used to provide an understanding of how the system responds to changes in freight demand. Therefore, considering the growth rate to adjust the data is considered relevant for this research.

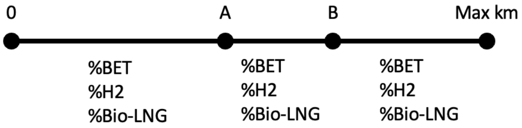

Figure 7.2: Explanation parameters

$$P_{node_i} = \left(\frac{X_{i,2030}}{X_{i,2019}}\right)^{\frac{1}{11}} - 1 \tag{7.1}$$

where,

P_{node_i} : Growth factor for node i
$X_{i,2019}$: Freight demand of node i in 2019
$X_{i,2030}$: Freight demand of node i in 2030

$$X_{i,2040} = (1 + P_i)^{10} \cdot X_{i,2030} \tag{7.2}$$

7.2.2. Additional Data

The freight data has provided insights into how the freight is transported over the roads in Europe. Besides this, it is important to dive deeper into their features to further understand the performance of alternatives fuels. A causal relationship diagram is made to determine which technical variables influence the system performance; the diagram can be found in B.1.1. In addition, the diagram visualizes how the metrics of the system are interrelated with the other elements in the system. Fuel consumption, travelled distance, station capacity, etc., are relevant inputs for the model. Existing research and features of current vehicles were used to determine the value of these inputs; these can be found in appendix B.

By doing a sensitivity analysis of the input variables, the sensitivity can be checked. This will be discussed further in the discussion, chapter 14. Checking the input variables can also be used to examine what properties of alternatives are important for improving the system. However, this is not within the scope of the study, and will therefore not be discussed further.

7.3. Model implementation

This section discusses the steps defined in 7.1 more in detail. The section addresses how the steps are implemented in the model.

7.3.1. Determination of input parameters

The model splits the freight data into three separate data sets. This is based on the value of 11 parameters; see figure 7.2. The model first generates a random value of A. After generation A, the model generates a random value between A and the max distance (18234 km)in the data set, which is the value for B. This ensures that all three ranges are connected and ensures that every distance within the data set is assigned to one of the ranges.

Besides a value of A and B, as shown in figure 7.2, the data is assigned for a specific percentage to an alternative within each range. So, for example, within the range from 0 to 500 km, 70% is assigned to BETs, 20% to Hydrogen, and 10% to Bio-LNG. These percentages have to meet the requirement to sum up to 100%. Otherwise, not all freight data will be assigned to one of the alternatives, and the system will not meet requirement 2.2 of table 3.1.

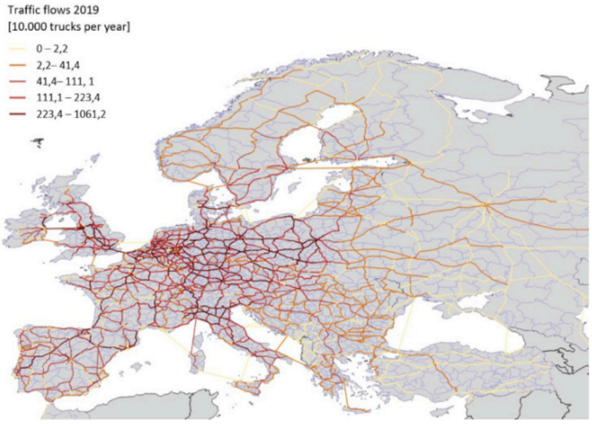

Figure 7.3: Total Truckflow Europe 2019 [59]

7.3.2. Road network

The model creates a graph. In this graph, the nodes are the freight data's origin and/or destination. The location of the nodes is the geographical location of these origin and destination. Based on the edge data, the model creates edges between the nodes. The model reads the freight data and assigns the truck flow to the graph's edges. The truck flow is the number of trucks that move between an origin and destination yearly. Figure 7.3 shows the total truck flow within Europe. The danker edges are the edges which are more congested freight areas.

After creating a total freight model, the model creates three new data sets based on the determined input parameters. These data sets are created based on the input parameters described in 7.3.1. Depending on the drive range and percentage, a trip is assigned to one of the alternatives. After that, the model creates a new graph for each of the alternatives. The model calculates the yearly truck flow over an edge per alternative.

7.3.3. Number of stations

After creating the freight simulation, weighted K-means must be used to determine the optimal location for refuelling stations. However, K-means doesn't specify the optimal amount of clusters (stations). As mentioned in chapter 6.2, the number of clusters is an input for the algorithm to determine the optimal location of the centroids of the clusters. There are different methods to determine the correct number of clusters. The number of clusters in this research depends on the demand for a specific fuel.

Since the truck flow and the total length of the edges are known, the model calculates the total kilometre per alternative travelled over the network. Multiplying this by the fuel use of the alternative will provide the total fuel demand of an alternative for the network. By knowing the capacity of a station, the total number of stations can be calculated by equation 7.3.

$$K_x = \frac{D_x}{C} \quad \text{where,} \tag{7.3}$$

K_x: Number of clusters of alternative x needed to cover the total demand

D_x: Total demand of alternative x in kWh/year

C_x: Yearly capacity of a refuelling station of alternative x in kWh/year

$$[Dimentionless] = \frac{[kWh/year]}{[kWh/year]}$$

$$C_x = \left(\frac{24}{t_{refuelling_x}} \cdot N_{pumps} \cdot 365 \right) \cdot C_{tank_x} \quad \text{where,} \tag{7.4}$$

$t_{refuelling_x}$: Refuelling time of alternative x in hours
N_{pumps}: Number of pumps at a refuelling station
C_{tank_x}: Capacity of a tank of a truck of alternative x

$$[kWh/year] = \frac{[Dimentionless]}{[hours]} \cdot [Dimentionless] \cdot [Dimentionless] \cdot [kWh]$$

7.3.4. Demand points

As described in 6.2, K-means use points, not edges, to create clusters. However, the graph has an edge with truckflow. The truck flow can be seen as a demand for a specific fuel. Therefore, the edges are transformed into demand points. Step one is determining the coordinates of the geographical centre of the two nodes of an edge, done by equation 7.5 and 7.6. Thereafter, the truck flow of that edge should be assigned as an attribute to that node, equation 7.8. This results in a new graph with the locations of demand points and the truck per km as attributes to the node.

$$x_{center} = \frac{x_a + x_b}{2} \tag{7.5}$$

$$y_{center} = \frac{y_a + y_b}{2} \tag{7.6}$$

$$F_d = \frac{F_e}{L_e} \quad \text{where,} \tag{7.7}$$

F_d: Yearly truckflow of demand point in truck/km/year
F_e: Yearly truckflow of edge in truck/year
L_e: Total length of the edge in km

$$[Truck/km/year] = \frac{[Truck/year]}{[km]}$$

Based on these demand points, the K-means algorithm can be used by the model. It divides the demand point into different clusters. The number of clusters is already determined and is an input for the algorithm. Each cluster has a centroid. The centroid is the centre of the cluster, which corresponds to the arithmetic mean of data points assigned to the cluster. The location of the centroid is the location of the refuelling/charging station. After determining the location, the stations are also located as nodes on the graph, see figure 7.5.

7.3.5. System Costs

The freight model and location of the refuelling/charging stations have provided the information that is needed to calculate the system costs. As mentioned in chapter 5, there are different types of costs: production cost, transport and storage cost, station cost, and vehicle cost. The cost equations can be found in the appendix B. The total system cost is determined by equation 7.8.

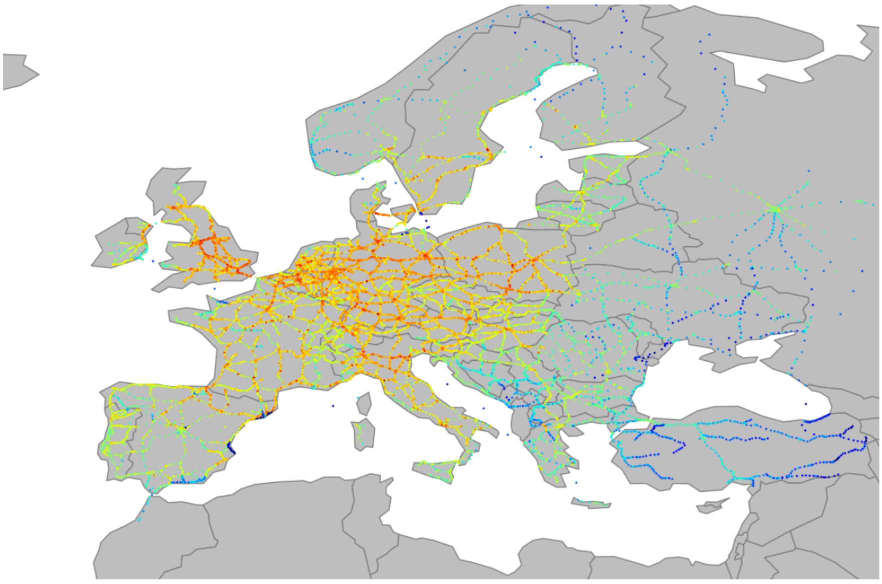

Figure 7.4: Example demand points

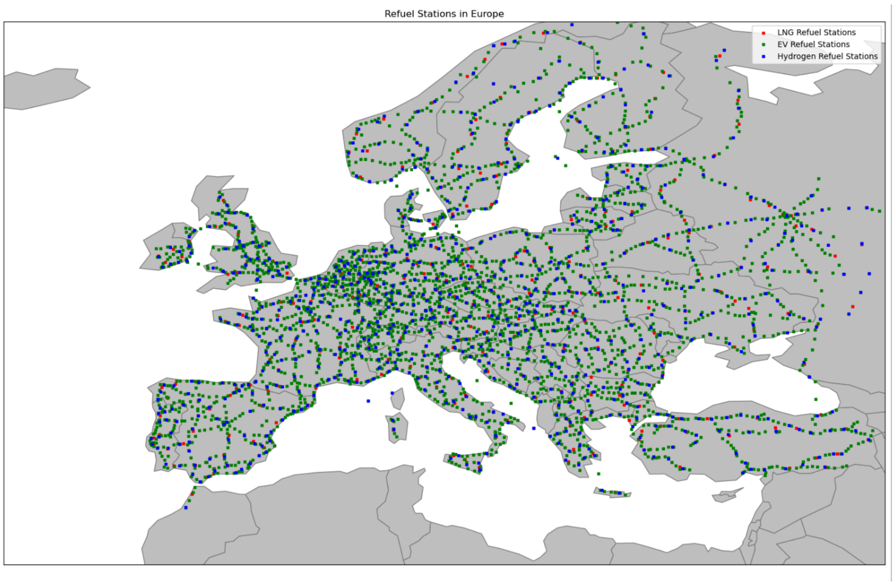

Figure 7.5: Station allocation

Table 7.1: Freight value of time across Europe [64]

Region	Value
Southern Europe	1.682 €/h-ton
Central Europe	2.592 €/h-ton
Western Europe	7.818 €/h-ton
North Europe	0.314 €/h-ton
Average	3.1015 €/h-ton

$$C_{\text{total}} = \sum_x \left(TC_{\text{production}_x} + TC_{\text{station}_x} + TC_{\text{transport}_x} + TC_{\text{vehicle}_x} + TC_{\text{punitive}_x}\right) \quad \text{where,} \tag{7.8}$$

C_{total} : Total system cost

$TC_{\text{production},x}$: Production cost of alternative x

$TC_{\text{station},x}$: Station cost of alternative x

$TC_{\text{transport},x}$: Transport and storage cost of alternative x

$TC_{\text{vehicle},x}$: Vehicle cost of alternative x

$TC_{\text{punitive},x}$: Punitive cost of alternative x

Besides financial cost and emissions, there is another technological difference between the alternatives: drive range and charging time. This would, for example, make BETs at longer distances less attractive. Due to the short drive range, the truck has to charge relatively often; in addition, charging also takes long. Therefore, this is an important aspect and should be considered in the model. To consider this, the time to refuel for each of the alternatives is expressed in monetary terms, using the value of time (VOT). Tao and Zhu [64] have determined the average VOT within freight transport for different regions worldwide, including Europe, see table 7.1.

Even though it is assumed that all alternatives have the same speed, the refuelling time of alternatives differs. The fees thus charged for recharging or refuelling will be seen in the model as a punitive cost. How these are calculated can be found in equation 7.9 and 7.10.

$$TC_{p_x} = \frac{c_{total_x}}{P_x} \cdot VOT \quad \text{where,} \tag{7.9}$$

TC_{p_x}: Punitive costs of alternative x in Euro

c_{total_x}: Total energy consumption of alternative x in kWh

P_x: Charging or refuelling power in kW

VOT: Value of time: $3.1015 \times$ average truck weight in tons

$$[Euro] = \frac{[kWh]}{[kW]} \cdot [Euro/hour]$$

$$c_{total_x} = \sum D_{\text{ij}} \cdot c_x \cdot F_{\text{ij}} \quad \text{where,} \tag{7.10}$$

D_{ij}: Distance between origin i and destination j in km

c_x: Fuel consumption of alternative x in kWh per km

F_{ij}: Truckflow between origin i and destination j

$$[kWh] = [km] \cdot [kWh/km] \cdot [Dimentionless]$$

Table 7.2: Tank to Wheel energy use alternatives [24]

Variable	TtW energy use, kWh/km
Diesel	2.74
Electricity	1.53
Hydrogen	2.93
Bio-LNG	2.74

Table 7.3: WtW GHG emissions, based on average European electricity mix [24]

Variable	WtW GHG emissions, g CO_2-eq/kWh
Diesel	320
Electricity	134
Hydrogen	384
Bio-LNG	32

BETs can be charged overnight at the origin or destination. The other alternatives must always fill up at a refuelling station. This gives the BETs an advantage over smaller distances. The model assumes that BETs start their trip with a fully charged battery. Therefore, if the distance of a trip is within the driving range of the BETs, the punitive costs are not taken into account for this alternative. If the trip is longer than the driving range, the punitive cost is considered from the moment that the driving range of the BET is exceeded.

7.3.6. Emissions

The system performance is measured by two types of metrics: cost and emissions. The emissions are taken into account to measure the impact of the transport movements on the climate. As described in the system description, chapter 5, for emissions, the WtW CO_2 are used. The WtW emissions consist out of Well to Tank emissions and Tank to Wheel emissions, these are also emissions associated with the fuel production for example. Using WtW emission gives a more comprehensive system perspective. The WtW emissions are in grams of CO2 per kWh. Therefore, to determine the total emissions of the network per alternative, the WtW emissions are multiplied by the total kilometre driven per alternative. The total system emissions are calculated by equation 7.11.

The emissions are based on the energy consumption of the vehicles, see table 7.2, and the WtW emissions, see table 7.3. These WtW emissions are based on the average European electricity mix. Since only 2% of the total hydrogen production is currently green hydrogen, hydrogen isn't currently more sustainable than diesel trucks. However, the European Commission has the ambition to produce and import a total of 20MT hydrogen in the near future [17]. Green hydrogen is considered carbon neutral and has much lower emissions.

$$E_{total} = \sum_{x}(WtW_x \cdot c_x) \quad \text{where,} \tag{7.11}$$

E_{total}: Total gram emissions of CO_2 of alternative x

WtW_x: Gram CO_2 emissions per kWh of alternative x

c_{total_x}: Total energy consumption of alternative x fuel in kWh

$$[gram] = [gram/kWh] \cdot [kWh]$$

8

Verification

This chapter initiates the verification phase. This ensures the reliability and accuracy of the model's outcomes. Verification checks if the model has been properly implemented. Therefore, the implementation of the code is checked, and the behaviour of the model is reviewed. Checking the implementation of the model is done by comparing the model with the method as described in chapter 6. Within freight modelling different steps are distinguished (as described in chapter 6). These steps can also be found within the model:

1. Production and attraction: The model uses the origin and destination from the data set of Speth et al. [59].
2. Distribution: The truck flow between the origin and destination is used.
3. Modal split: This step is not performed. Since the scope of the research is only road transport. In addition, the data set only includes data about road freight transport. Therefore, this step of freight modelling is not needed within this research.
4. Assignment: The yearly flow of trucks is assigned to the network. Where the nodes are origin and destinations, and edges have a representing truck flow as an attribute.

After the freight model, location optimisation is used by K-means. The model uses the K-means clustering algorithm from a module in Python. The model determines the number of clusters based on the fuel demand. Therefore also this part of the model is implemented correctly, as stated before.

8.1. Verification of model behaviour

In addition to the implementation, the behaviour of the model is checked. This section will look at whether the behavior shown by the model is logical and explainable. Therefore, the model results of 4 scenarios are compared, where the input parameters are the same for each scenario. The same scenarios, as described in chapter 9 are used. In this way, the behaviour of the model can be reviewed. Figure 8.1 shows a graph of the costs and emissions of the system for four scenarios. It shows that in each scenario, the same input parameters result in different costs and emissions for the system.

First of all, scenario 1, in this scenario, there is no growth of freight and there is no technological development of the alternatives. If we compare scenario 1 to scenario 3, there is also no technological development of the alternatives but there is growth in freight. We see that the emissions and costs are both increasing. Growth of freight means more movement of goods and, therefore more kilometres travelled. If there is no improvement of technology this means that the emissions increase and also the cost increase. Since both costs and emissions are associated with the total distance travelled.

If scenario 1 and scenario 5 are compared. In scenario 5 there is no growth of freight, but there is improvement in the technologies of the alternatives. The emissions and cost of scenario 5 are lower than the emissions and cost of scenario 1. Since there are no more goods transported but there is an improvement in technology, therefore they become cheaper and more sustainable.

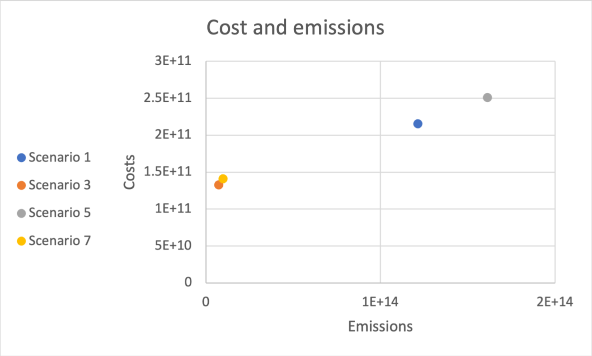

Figure 8.1: Verification model behaviour

In scenario 7, there is growth in freight and technological development. This means that the cost decreases and also the emissions. However, due to the growth of freight, the cost and emissions are higher than in scenario 5.

In conclusion, the results of the 4 scenarios compared, the results of the model shows expected and explainable behaviour. Comparing the four results from different scenarios, the model shows behaviour that can be logically explained. This, coupled with the proper implementation of the different steps within the model, shows that the model is sufficiently verified and, thus, properly implemented and compliant.

9

Scenarios and experiments

In the dynamic landscape of the freight road transport sector, the future is a vast realm of uncertainty and unpredictability. Nevertheless, future developments have an impact on the performance of the system. Therefore, this chapter will identify possible future scenarios. These scenarios can be used to analyse the model's performance under different conditions. Experiments within the scenario space provide the possibility to look for a solution that works well in many cases and is, therefore future-resistant. This chapter will answer research question 4: *What are the future projections for the growth and technology of electric, hydrogen and bio-LNG trucks in the road freight industry in Europe?*

9.1. Scenarios

External effects are used to identify scenarios. External effects are the forces that affect the system autonomously. This could be an infinite number of factors. To consider which factors to include or exclude, the external effects that have high uncertainty and high impact on the system are taken into account for the scenario analysis. The analysis, which can be found in appendix C, shows three external effects that are used for the scenario analysis and experiments.

9.1.1. Technological development

First of all, the technological development. Technological development often occurs independently. The industry anticipates and adopts existing technologies, but the direction of the technological process is inherently uncertain. While the road freight industry may not directly control technological developments, it can influence it through investments in research and development (R&D). Nevertheless, the control of technological development is partial, and it must operate within a broader technological ecosystem. Additionally, there is still a level of unpredictability and uncertainty inherent in technological development. Therefore, the development can't be influenced only by investments.

Besides the fact that technological development is unpredictable, the impact of technological development on the system is huge. Aspects of the system, like the vehicle's driving range and energy consumption, highly affect the performance of an alternative and the system. Therefore, this external effect is considered for the identification of the scenarios. Two different scenarios can be distinguished: No technological development (current state) and technological development.

The scenarios, as defined in this thesis, are all or nothing regarding technological development. This means that all inputs defined for technological development change simultaneously. This, therefore, assumes that all alternatives will improve. The input variables will be adjusted according to table C.3.

9.1.2. Freight demand

The second external effect is freight demand. This is an external factor because it is influenced by too many factors in the world that make it highly unpredictable. The economic crisis in 2007 and the pandemic in 2020 were unforeseen, but both caused effects on freight demand at that time. If the trend

Table 9.1: Identification of scenarios

Freight	Technological	Availability	ID
No growth	No development	Infinite	1
		Limited	2
	Development	Infinite	3
		Limited	4
Growth	No development	Infinite	5
		Limited	6
	Development	Infinite	7
		Limited	8

of freight is followed, the expectation would be that freight will continue to grow. To consider freight demand growth, the truck flow for 2040 is used. This is modified data, as described in chapter 7, based on the data from 2019 using a growth rate.

Despite the expectation that road freight will continue to grow in the coming years, there are also initiatives to reduce freight demand for the road due to emissions pollution. In part, by encouraging rail transportation and local production, the freight that must be transported by road can also possibly stagnate in the coming years. Due to the unpredictability of the freight demand, it is important to note that this growth factor was mainly used to control the effect of freight growth on the system and alternatives, rather than predict the future. Therefore, experimenting with the growth of freight improves the understanding of the system.

9.1.3. Availability of alternatives

In addition to the external factors, economic growth and technological development, the availability of different alternatives significantly impacts the overall system. It is crucial to recognize that not every alternative is inexhaustible, leading to a nuanced exploration of their feasibility. Take Bio-LNG, for instance, Bio-LNG is made out of waste. However, waste availability is finite, limiting the widespread adoption of Bio-LNG. The expectation is that by 2050, the supply of Bio-LNG will be about 1170 TWh, 50% of which will be used as bio-LNG for the heavy-duty transport sector [6]. So, the available bio-LNG supply for heavy-duty transport is 585 TWh yearly.

Similarly, in the case of hydrogen, hydrogen is also seen as a very prominent alternative to fossil fuels. However, currently, only 2% of all hydrogen is sourced from environmentally friendly, ”green” methods. For hydrogen to be deemed a truly sustainable alternative, it necessitates a substantial increase in green hydrogen production. Consequently, the finite availability of green hydrogen becomes a crucial consideration in evaluating its role in future scenarios. The EU has set a goal to increase the production of green hydrogen. The EU strives to achieve a supply of twenty million tons (20Mt) of green hydrogen by 2030 – 10Mt produced and 10Mt imported per year [30].

Finally, electricity. The possible problem for the charging infrastructure for BETs is the electricity grid. Currently, the energy network is already overloaded and there is no space available on the electricity grid. The model takes this into account by determining costs for its expansion. Expanding the electricity grid is necessary not only for making freight transportation more sustainable, but also for the continued energy transition. The grid expansion costs are considered as transport cost for the BET alternative. As described in chapter 5, hydrogen en Bio-LNG are transported by truck, and the associated transport costs are determined as described in chapter 5.

In addition, in 2021 about 22% of the produced energy in Europe is produced by renewable energy sources [12]. Although renewable energy production is expected to increase in coming years, it is also not infinitely available. However, as shown in table 7.3, the use of electricity is currently more sustainable (with the current electricity mix) than the use of diesel, as opposed to grey hydrogen. Therefore, for BETs, available green energy is not included as a limiting factor.

This results, in combination with the technological development and freight growth, into eight scenarios for this research; these can be found in table 9.1. The adjustment of the input variables for the scenarios can be found in appendix C. The following section will address the experimental setup.

9.2. Experimental set-up

To explore the implications of the diverse scenarios outlined in the preceding section, this section discusses the experimental setup. Within each of the scenarios, the experiments provide insights into the performance of the system under the change of parameters. As discussed earlier, the system has parameters used to perform the experiments. By adjusting the input parameters, the performance of the system can be tested. First, the model is run for each alternative individually. In addition, to test the effect of the range for each alternative individually, the driving range intervals will be adjusted for each alternative. Lastly, the effect of the VOT was tested by increasing this value.

9.2.1. Alternatives individually testing

First, the model is tested for the use of each alternative individually. This experiment checks the system performance when the entire road transport system uses only one of the alternatives. It enables the comparison of the different alternatives on a network level. Even though this is not the primary research goal, on the contrary, there have been comparisons of the alternatives in previous research, it is still important to compare the alternatives individually. Because it provides a better understanding of why specific runs in which combined alternatives perform better or worse. Furthermore, it provides insights into the cost proportion of the alternatives, which is helpful for the policy implications.

The alternatives are tested individually by assigning 100% of all three distance intervals to one alternative. This ensures that all trips contained in the data set are assigned to just one alternative. Because the entire diesel network is already available, it is not possible within the scope of this study to compare the costs of the alternatives with those of diesel. Therefore, the costs of the alternatives will be compared among the use of BETs, Hydrogen trucks and Bio-LNG trucks. The emissions of the alternatives can be compared with those of diesel in the results chapter.

9.2.2. Kilometre distance range

To explore the system performances for combining alternatives over different trip distances, experiments are conducted for adjusting the drive range intervals. These experiments are designed to assess the cost-efficiency of different fuel alternatives within specific driving ranges. It examines whether it is beneficial to use for shorter distances BETs, for example, and for longer distances one of the other alternatives, as might be expected according to previous research. If any of the alternatives prove to be more financially advantageous at specific distances, it is important to identify these optimal distance thresholds for each alternative. The insights can be used to guide stakeholders in the use of the alternatives.

The first range interval is considered to be 0-250 km, and the longest tested distance is 4500-5000 km. The data does not have enough cases for distances bigger than 5000 km to make a sufficient network. The model uses all trips for which the distance falls within this interval and creates a network for each alternative. After that, the model determines the costs of the system for each of the alternatives. To compare the alternatives the cost per kilometre is determined. The used ranges are shown in appendix C.1. These interval experiments aim to explore the performance of the alternatives over different distances.

9.2.3. VOT experiments

Finally, experiments are conducted in which the value of time (VOT) is increased. The value of time depends on what goods are being transported. High-priority goods or goods that have a shelf life may have a higher VOT because, for these products, it is important to arrive on time. Within the previously described experiments, the average VOT for road freight is used. By increasing VOT, time becomes more important within the system. By increasing VOT, the refuelling time plays a more prominent role in system performance. For example, longer refuelling times will result in a higher cost of the alternative. This might influence the trade-off between the alternatives over the distance. Thus, it is important to understand the sensitivity of the system for the VOT.

Therefore, these experiments are designed to yield insights into the sensitivity of the model concerning VOT fluctuations. This is essential to understand the balance between time efficiency and cost efficiency. The outcomes are expected to facilitate a more nuanced understanding of the interplay between VOT and the alternative choice. In the VOT experiments, the drive range intervals, as defined in

9.2.1, were also varied to understand the effect of these adjustments over different distances.

This chapter has identified eight different scenarios that incorporate technological development, freight demand and limited supply of alternatives. In addition, this chapter has discussed several experiments that will further enhance understanding of the system. The next chapter will discuss the results of the experiments and compare the different scenarios.

10

Results

This chapter presents the results of the experiments that were conducted as described in chapter 9. Further, it will briefly discuss what the results mean. Comparing the outcomes of the experiments and scenarios provides insights into the system's behaviour. Chapter 12 will further describe what these results mean regarding policy implications.

This chapter answers research question 3: *What is the effect of the alternatives on the network in terms of costs and emissions?* In addition, this section will also provide an answer to research question 5: *What is the effect of the projections on the road freight network in terms of cost and emissions?* This chapter will discuss the effect of the different alternatives on system cost and emissions by first comparing them individually. After that, the results of combining the alternatives will be discussed. Furthermore, based on the scenarios and experiments, the effect of the future projections will be discussed.

10.1. Comparing alternatives individually

In the first experiments conducted, costs and emissions for each alternative are considered individually. Here, there is no restriction on the availability of alternatives. The model is run for the current situation. Furthermore, the freight growth and technological development projections are tested (scenario 7). This experiment aims to compare each of the alternatives and better understand how the costs are divided within the total cost of the alternative individually.

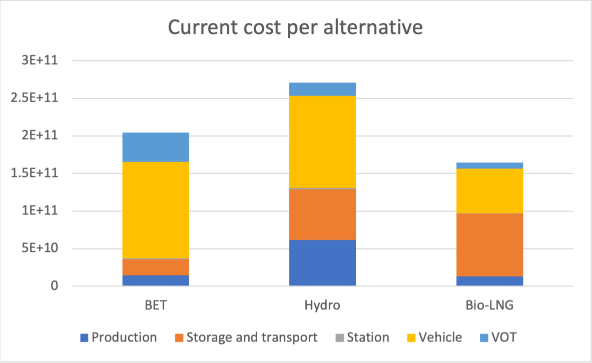

Figure 10.1: Current cost per alternative

The system would be most cost-effective if the system would remain using fossil fuels. However, if doing so, it can not ensure other system requirements. Figure 10.1 shows the current costs for shifting to a singular alternative. If the alternatives for fossil fuels are compared, the Bio-LNG would currently have the lowest cost. Within the costs, it is notable that a relatively large portion of the costs go to vehicle costs. This applies to all alternatives.

Furthermore, the penalty cost of refuelling time (VOT) is highest for BETs. This is explained by the relatively short drive range of BETs in this scenario. Furthermore, recharging for BETs takes longer compared to refuelling the other alternatives. However, without considering the penalty cost for charging, BETs still aren't competitive with Bio-LNG trucks, but the difference between these alternatives decreases. The performance of BET might, therefore, be influenced by the value of the VOT. The impact of the value VOT is further elaborated in 10.4.

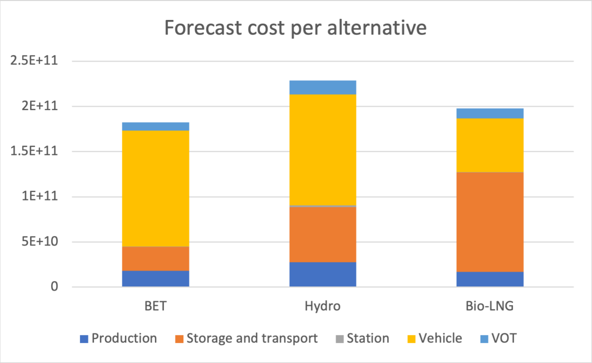

Figure 10.2: Forecast cost per alternative

Figure 10.2 illustrates the costs, including the development of the alternatives and freight growth. This figure also shows the distribution of the costs. When this figure is compared with figure 10.1, the cost difference between the alternatives decreases. In addition, the BET alternative becomes cheaper than Bio-LNG. This is partly because penalty time decreases with MegaWatt chargers and batteries with a more extensive driving range. In addition, it is noticeable that the production costs for hydrogen in the proportion relatively decrease.

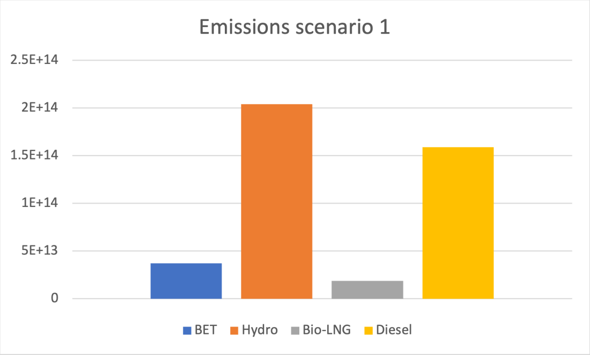

Figure 10.3: Current emissions per alternative

Figure 10.3 presents emissions in the current situation of freight demand and technological development. Hydrogen is the least advantageous in terms of emissions. Hydrogen is performing worse than diesel in terms of emissions. The emissions of hydrogen are currently this high because only 2% of the hydrogen is green in this scenario. The rest of the hydrogen is grey and, therefore, more polluting than diesel. As a result, hydrogen is currently not a sustainable alternative to diesel, as the figure shows. However, the other two alternatives are already significantly more sustainable than diesel. However, not all energy for charging BETs is produced sustainably. Therefore, the emissions are higher than for Bio-LNG.

Comparing figures 10.3 and 10.4 provide insights into how emissions change from the alternatives as the technology developments and the freight demand increases. In this, it is especially notable that hydrogen is becoming significantly more sustainable than before technological development. When produced completely green, hydrogen proves more sustainable than Bio-LNG. Finally, BET emissions are the lowest in the future scenario.

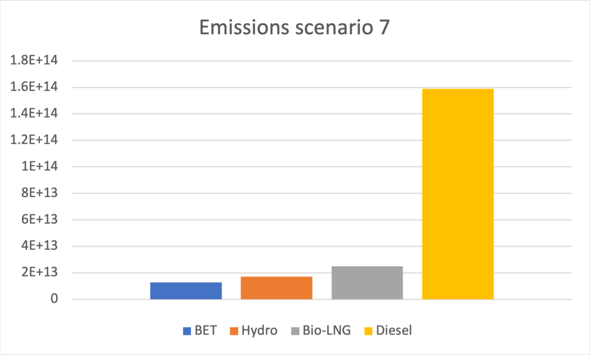

Figure 10.4: Forecast emissions per alternative

From the results of the experiments testing the alternatives individually, it can be concluded that Bio-LNG can currently be seen as a relatively good alternative to fossil fuels. In the current situation, hydrogen is not a potential alternative due to high emissions from using grey hydrogen and high costs. However, its potential changes when green hydrogen is used, and developments occur as expected. Then hydrogen becomes a more interesting alternative to consider in terms of emissions. However, the cost remains relatively high. BETs seem to be a middle ground between the two alternatives. In the current situation, the costs are not the highest but become lowest when it develops further. Emissions are also already significantly lower today than using diesel. So, this would also be an alternative to consider with and without further technological development. However, considering the technological development, the performance of BETs would be the most promising.

10.2. Alternatives per range

The following experiments tested the driving range for each alternative. The model was run for each alternative for 11 ranges, from the smallest range interval of 0-250 km to the furthest distance range interval of 4500-5000 km.

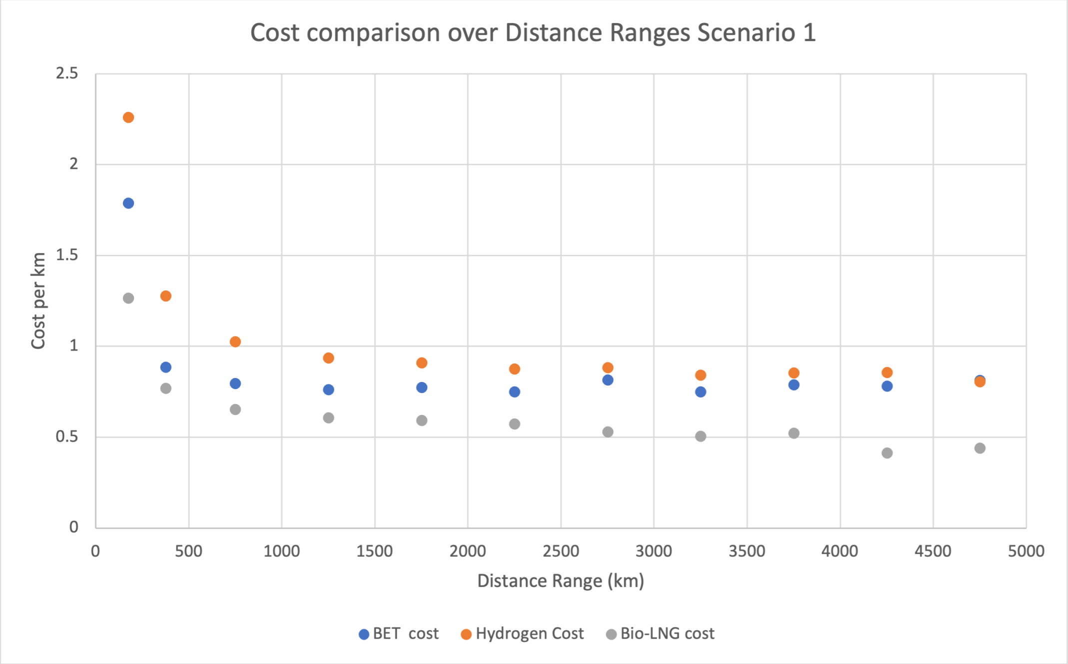

Figure 10.5: Cost comparison over distance range scenario 1

Figure 10.5, shows the results for scenario 1. The chart points are placed in the middle of the range. All alternatives start with relatively high costs that rapidly decrease. Truck and station costs can explain this; high investments are made for fewer kilometres. This indicates economies of scale, which is in line with previous research [1]; however, it should be tested further to drawn this conclusion. It is also noticeable that the order from most cost-effective to last cost-effective does not change over the distance intervals. Regardless of the range distance interval, hydrogen remains the most expensive, followed by BETs, and Bio-LNG is the cheapest in scenario 1 (current situation). From this, it can be concluded that for scenario 1, combining alternatives in the European road transport network is not advantageous over using one singular alternative over all distances.

The order between the alternatives in terms of cost does not change. However, the distance between the chart point for the alternatives over the distance intervals does change. For the current situation (scenario 1), hydrogen is relatively expensive and has too many emissions to compete with the other alternatives. Therefore, the focus will be on comparing the other two alternatives in this scenario. As the distance range gets longer, the difference between the cost per kilometre between Bio-LNG and BETs increases. This means that for longer distances, it is more cost-effective per kilometre to drive on Bio-LNG. For the very longest distances, BETs are as expensive as hydrogen. Thus, using Battery BETs for shorter trips might be advantageous, ensuring sufficient Bio-LNG is available for longer trips where Bio-LNG proves more relatively cost-effective.

The range experiments were also run for a future scenario (scenario 7) to compare with the current scenario (scenario 1). The results where the entire system was run for a single alternative, shown in 10.1, show that using BETs in the future becomes more advantageous than using Bio-LNG. These experiments aim to verify if this observation holds across all distance intervals.

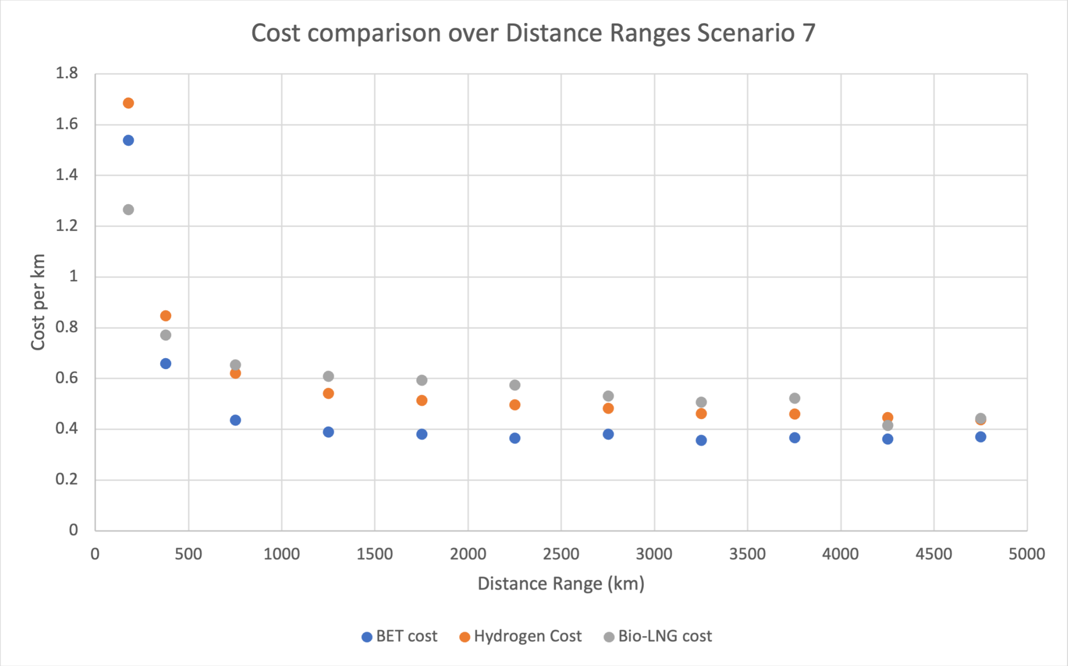

Figure 10.6: Cost comparison over distance range scenario 7

The results are shown in figure 10.6. In both scenarios, the cost per kilometre generally decreases as the distance range increases. For almost every distance range, except for the shortest range, due to the relatively high vehicle costs, BETs perform as the most cost-efficient. Bio-LNG performs as the cheapest alternative for the shortest distance due to the relatively low vehicle cost of Bio-LNG. Furthermore, the results in figure 10.6 show that the cost for Bio-LNG on the shortest distance is the cheapest and the most expensive for the medium ranges. For distances bigger than 4000 kilometres, it would be advantageous to use Bio-LNG over Hydrogen.

In conclusion, based on the individual testing and range distance interval testing, it can be concluded that combining alternatives within the road freight network is not more beneficial than using a single alternative in terms of costs. Still, using the alternatives (with grey hydrogen excluded) combined or individually in terms of emissions is better for the system than diesel.

10.3. Availability of alternatives

As mentioned in the literature review, chapter 4, availability is a constraint for alternatives. Therefore, the model also determines how much alternative fuel would be needed per distance range and, therefore, calculates the fuel demand for the network. These results can be found in appendix D.4.

The projection of 20Mt of green hydrogen production annually aligns with the European targets, signifying that hydrogen's availability will not be a bottleneck for its utilization as a singular fuel source, provided that the targets are met. Conversely, the current production of green hydrogen at 11.5 Mt, constituting merely 2% of the projected requirement, underscores a significant shortfall, making a hydrogen-only approach unfeasible under the current circumstances.

In contrast with hydrogen, only relying on Bio-LNG would probably be impossible, because there will be a shortage. Thus, Bio-LNG must be integrated with other fuels to ensure a consistent and reliable supply of alternative fuels in road freight transport. Bio-LNG, derived from bio-gas processing, has a production capacity that is inherently constrained by the availability of its organic feedstock. Based on the results in figures 10.5 and 10.6, and the findings of insufficient demand for Bio-LNG, it would be beneficial in the current situation to stimulate the use of Bio-LNG for long-distance trips. The difference in price per kilometre between the alternatives is greater on long distances. This suggests that despite the limited availability of Bio-LNG, there is a financial incentive to promote the use of Bio-LNG for long-haul trips.

It is important to emphasize that using BETs requires the expansion of the European energy grid. In the model, this is included as costs. Therefore, it is not further included as a limited factor within the system. However, the grid must be expanded; otherwise, it will be impossible to build a charging infrastructure.

10.4. VOT

Finally, the last experiment examined the model's sensitivity concerning the cost of charging using the VOT. The value of time depends on the product being transported. Products of higher value with a short shelf life have greater importance to arriving earlier at a location, increasing the value of time. The Monte Carlo simulation used an average time value for freight transportation. However, since the VOT can vary, it is helpful to test the sensitivity of this input variable. Thus, in these experiments in which VOT is varied, the VOT was increased while keeping the other variables constant and then compared. These experiments were also run for two scenarios: scenario 1 (current situation) and scenario 7 (including future projections) because these scenarios allow us to compare the current situation and future development in terms of technology and freight demand. The cost per kilometre is determined over a set of distance ranges to analyse the results, like the experiments in 10.2.

In figure 10.7 are the results presented of increasing the VOT with 50% for scenario 1. The results show that Bio-LNG is the cheapest per kilometre for each distance range. The difference increases with distance. In addition, it can be seen that alternative hydrogen and BETs intersect. From a distance of 1500 km, it becomes more advantageous to drive hydrogen. Thus, when the VOT becomes higher, the attractiveness of using hydrogen increases (compared to BETs). Because the refuelling time of Hydrogen is shorter, and a truck can drive further on a hydrogen tank than with a battery.

Figure 10.8 shows the results for scenario 7 in which the VOT is increased. Here, it is noticeable that the performance of all alternatives is more similar than in figure 10.6. Especially at the longer distances the cost per kilometre doesn't differ much between the alternatives.

When comparing the figures in 10.2 to the ones in which the VOT is increased, it is notable that, especially in scenario 1, the performance of BETs is decreasing and, therefore, isn't performing well (in terms of cost) at longer distances. For scenario 7, it is notable that the model's behaviour doesn't change much if the VOT is increased. Therefore, the model in scenario 7 seems less sensitive to changes in VOT. This can be explained by the fact that less time is spent refuelling in scenario 7, regardless of which alternative, which reduces the overall effect of change in this variable.

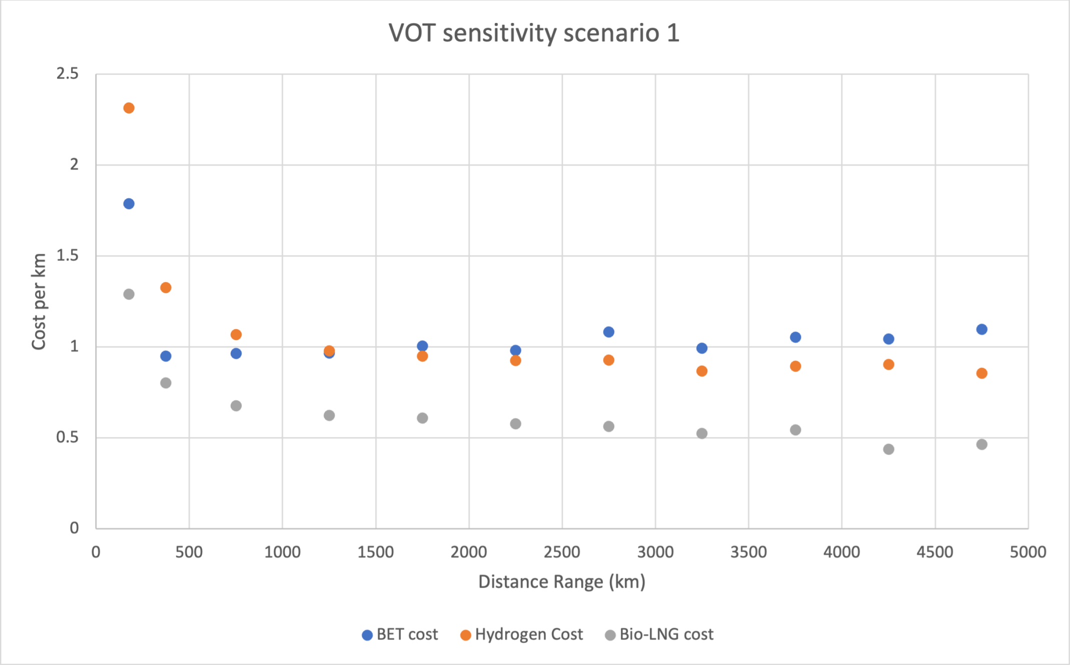

Figure 10.7: Sensitivity VOT scenario 1

As alternative technologies evolve, the impact of penalty costs diminishes, making the system less sensitive to variations in the VOT in future scenarios. However, this presupposes successful technological advancements. Should these developments lag, particularly in a context of high VOT for freight, BETs may prove less viable for long-haul journeys exceeding 1500 kilometres. Under these circumstances, the cost per kilometre for BETs becomes significantly higher, indicating their limited suitability for such distances.

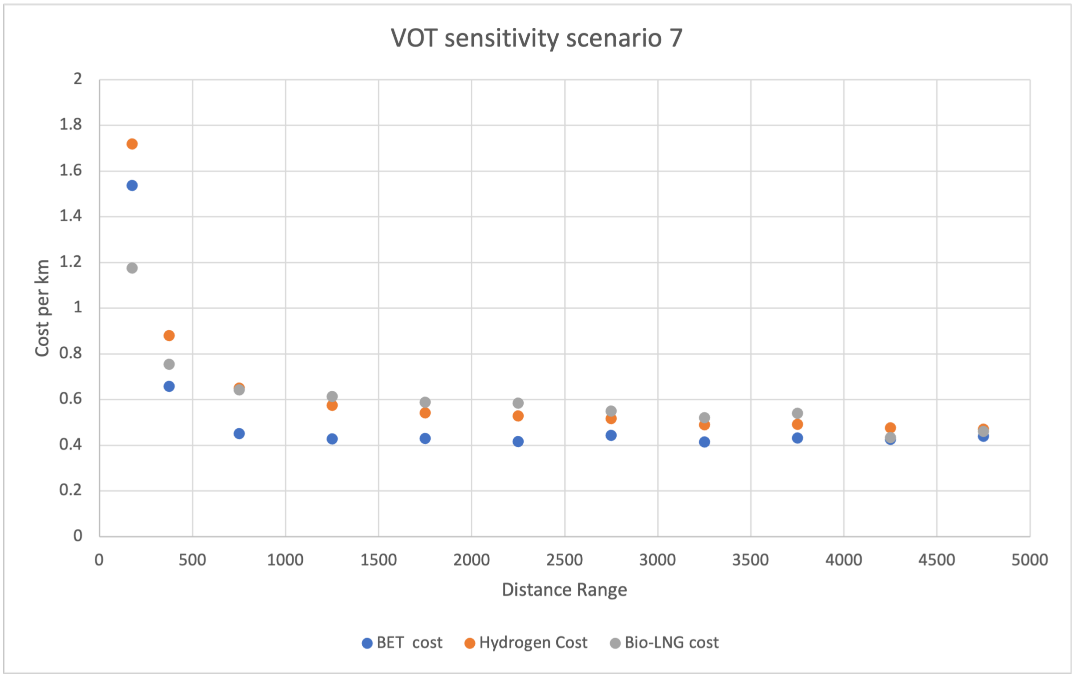

Figure 10.8: Sensitivity VOT scenario 7

11

Validation

Validation involves checking whether the model is sufficiently consistent with empirical observations. In other words, whether the model sufficiently matches reality. If the model is not valid, it does not say enough about reality, and the result aren't valid. There are several methods for checking whether the model is sufficiently valid.

For the validation of this thesis, the results are compared with the results of the real world. Because the rollout of the different alternatives has not yet taken place, the results of the diesel model are compared with real-life data. In 2021, 740 million tonnes of carbon dioxide were emitted by transportation in the European Union; about 27% of this came from heavy-duty trucks and busses [52]. This is a total of 199.8 million tonnes of carbon dioxide. The created diesel model calculates a total of 158.9 million metric tons of carbon dioxide emissions within the system with the data of 2019. This means that my model calculates 20% lower emissions than in reality. However, this 20% could be partly explained by the fact that also buses are included in the real-life data and not in the model. The purpose of the study is taken into account; the goal is to understand the behaviour of the model. The model provides sufficient direction to be valid. Nevertheless, it is important to keep the difference between reality and the model in mind when interpreting the results.

The model is further validated in an interview with the European Alternative Fuel Observatory (EAFO). The model has run for each of the alternatives individually to explore the performance of the alternatives without any restrictions. The results are presented in figure 11.1. The results show the potential of Bio-LNG. However, Bio-LNG is limited available, which makes investing in it risky. In the current situation, with the current prices and development of the technology, there is more potential for BETs than for hydrogen in terms of cost and emissions.

During the interview, the representative of the EAFO said that they currently do not actively influence

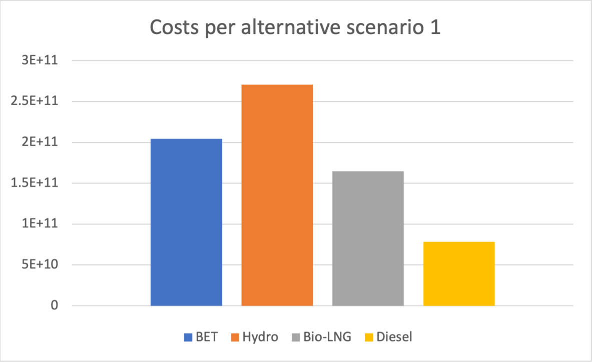

Figure 11.1: Cost per alternative

the system to support one alternative over the other. They are focused on providing information and data to the sector. What currently happens in the market is just market forcing. The EAFO stated that they see the market move more and more to BETs. This is in line with the results of the alternatives. Since the prices of the BETs are currently lower than hydrogen, they aren't limited by a limited supply. Therefore, it is a relatively safe alternative to invest in. This validates the model further.

11.1. Reflection on System requirements

A systems analysis was performed in chapter 5. System requirements were identified and shown in table 3.1. Reflecting on these requirements and checking whether they are adequately ensured can further validate the model.

For model validation, it is essential to distinguish between requirements that can be ensured by the model or requirements that can be met through policy. The requirements ensuring the system's long lifespan and national acceptance must be further ensured through policy. Thus, that will not be discussed further in this model validation, but this will be discussed in chapter 12. The model provides insights into the costs and emissions resulting from the various inputs. Thus, the model does not optimize for costs or emissions but provides insights into what they are under different conditions. A policy can then guide how to achieve these inputs and, therefore, the desired results.

The first two requirements have to do with limiting costs. On the one hand, by getting the number of stations as low as possible and on the other hand, by getting the total cost of the system as low as possible. These requirements must not conflict with the requirement that ensures that the total freight and fuel demand is met. The model guarantees a limited number of stations and an adequate fuel supply. Limiting the number of stations is guaranteed by how the number of clusters is determined. As a result, the number of clusters equals the number of stations needed, considering the average capacity of a station and fuel consumption.

Enough fuel supply is considered within the scenarios where alternative availability is considered. In case the demand for any of the alternatives exceeds the expected availability, a new random value is generated where demand can be met. This ensures that the demand for an alternative fuel does not exceed its supply.

Finally, the model ensures that all the freight in the data set is transported. This is achieved by aligning the ranges: from 0-A km, from A-B km and from B-max km. As a result, all distances of trips are assigned to one of the ranges. In addition, the distributions of the alternatives within the ranges should be summed neither more nor less than 100%. This assigns all trips in the data set to one of the alternatives. Therefore, this ensures that the requirement of transporting all freight can also be met.

This chapter has focused on the validation of the model. It can be concluded that the model is valid despite the difference between reality and the model. The next chapter will discuss what the results mean for policy on this topic.

12

Policy implications

By analyzing the results, recommendations in terms of policy can be provided. This chapter dives deeper into the policy implications. The different scenarios show what happens to the costs and emissions of the system under other conditions. Based on these results implications of policies can be provided. The EC does have a variety of tools to influence the system. This chapter will describe some of these tools and substantiate their suitability for this system by reflecting on the system requirements. The conclusion of this chapter answers research question 6: *What types of policies are required to use the refuelling network?*

It is essential to understand the context to properly explore the possibilities of implementing the policy; therefore, briefly return to the system description, see chapter 5. Firstly, the stakeholders and how they relate to each other. There are three key stakeholders identified; the EC, oil and gas companies, and transportation companies. These stakeholders have the power and interest in the system. Importantly, there is inherently little incentive for oil and gas companies and transport companies to invest in sustainable alternatives. Especially since these investments are high and the alternatives are still being developed. This may result that the other options will be much better within a few years. This explains the hesitant attitude of the sector.

Unfortunately, climate change does not wait for these developments. Therefore, it is crucial that investments are already being made in the sustainability of this sector. In addition, there is another problem in developing an infrastructure: the chicken and egg problem. In short, if there is no refuelling station infrastructure, transport companies will not buy trucks to run on it. But no infrastructure will be built if no trucks run on alternative fuels. The lack of incentives from stakeholders and this chicken-and-egg problem highlights the importance of the EC stepping in.

Although the results show that combining alternatives in the system is not beneficial over using a single alternative, in the future, when green hydrogen is used, all alternatives result in less environmental impact. As the results show, focusing primarily on developing a BET infrastructure is advantageous when considering future technological development in terms of cost and emissions. However, BETs are not the cheapest alternative currently. As a result, the industry will be hesitant to make the switch, preferring to wait a few more years until the vehicles achieve the desired performance and lower costs. Therefore, it is necessary that the national governments and EC now further stimulate BETs. Furthermore, the results in 10.2 show that if BETs aren't taken into account, the two other alternative switches in cost-effectiveness over the ranges.

The performance or the system is hugely dependent on the technological developments of the alternatives. This is uncertain. Therefore, betting entirely on only one alternative is too risky. Therefore, the EC would do better to focus on rolling out a charging infrastructure, while not trying to exclude the other alternatives from the market.

12.1. Types of policy

So far, policies regarding alternatives have been relatively general, consisting mainly of targets rather than restrictions or the creation of incentives. However, the urgency of the problem is high, and the incentives from industry are too low. The results show that the current cost for a system that runs on the cheapest alternative is still twice as high as a system that runs on diesel. Therefore, it is necessary to develop explicit policies to develop sustainability within the road freight sector further.

Overall, two forms of regulation can be applied to this system. On the one hand, limiting emissions by restricting the amount of emissions from transportation companies and oil and gas producers. On the other hand, emissions can be limited by stimulating alternatives to fossil fuels in road freight transport. As stated before, this thesis focuses on the infrastructure and assumes that the EC can, by developing the infrastructure, stimulate one of the sides of the market, and can solve the chicken-and-egg problem.

12.1.1. Restriction

First, the regulation through restriction. System emissions can be reduced by placing restrictions on transportation companies and oil and gas producers. However, this study focuses on infrastructure, so restrictions on transport companies are outside the scope of the study.

Restrictions are possible for oil and gas companies. This can be done by mandatory closure of diesel/-gasoline service stations. However, cooperation between the stakeholders within this system is essential, and the compulsory closure of gas stations can create a lot of resistance. In addition, this restriction can have an impact on the national acceptance of the road network. Therefore, not meeting requirement 3.3 may become a reality.

Another option is less radical: to indirectly restrict these companies by setting a maximum amount of emissions for them. The EC can use fines in case of exceeding these limits by companies. In line with the emission restriction, another possibility would be to levy additional taxes on environmentally unfriendly alternatives. The effect may be that gas stations which supply diesel or gasoline disappear from the system. However, this does not immediately cause replacement by sustainable alternatives. As a result, an insufficient refuelling network is one of the requirements for this system. Therefore, policies using restrictions are considered ineffective for this system; thus, these policies don't result in a preferable system.

12.1.2. Incentives for the development of the infrastructure

To solve the chicken and egg problem, one side of the market needs to be stimulated, because incentives of both sides of the market are missing. Since driving with alternatives without suitable infrastructure is impossible, this research has focused on developing the infrastructure. There are several options to achieve this.

The first possibility is funding. The connectivity for a system like this is essential. Otherwise, the system can't meet the requirement to be reliable. Therefore, developing the infrastructure within European Union member states is essential. The EC could incentivise local action to stimulate this development, such as through conditional funding. By conditional funding, oil and gas producers can be stimulated further to invest in alternatives. The EC can make funds available when member states meet specific requirements, such as realising a certain number of charging stations. Attached to this can be an obligation for member states to use this to reduce the land rent of optimal locations for charging stations. This ensures the infrastructure's development and aligns the stakeholders' private and public interests.

Currently, using BETs is not the most potential alternative, mainly due to the long charging times and high vehicle costs. If BETs had shorter charging times, they could better compete with Bio-LNG trucks. Therefore, Mega Watt chargers must be realized. The EC can also play a role in this, particularly in promoting the standardization of charging points; this ensures interoperability across different countries and systems. The standardization of charging systems also improves the accessibility of the system.

As described earlier, the European energy grid is overloaded and expansion is needed. Not only to

Table 12.1: Policy objectives

Research results	Intervention needed	Policy	Objective
Need for alignment of stakeholders	Yes	Communication and education	Transparency of the market and development of alternatives. Creating incentives to invest in alternative fuels in road freight transport because of the potential market development. In addition, it limits the risks of sunk costs, and therefore, the created transparency will limit barriers for the stakeholders.
The future potential of BETs	Yes	Investing in grid extension	Grid extension is needed to facilitate the charging infrastructure for BETs.
		Conditional funding/ subsidizing	Stimulation of infrastructure development at strategic places to ensure the network's reliability. In addition, this policy ensures standardization of the network and improves accessibility.
		Communication of potential	Removing the image of BETs being unsuitable for long-haul freight trips. Therefore, this policy should take away barriers for transport companies.
The limited potential of Hydrogen	No		
The current potential of Bio-LNG	No		
High proportional vehicle costs	Yes	Subsidizing sustainable HDTs	To stimulate the affordability of vehicles that run on alternative fuels. Ensuring that investment in these trucks by transport companies does not wait until further development.

facilitate charging points for BETs but also for the further energy transition. The model includes the expansion of the energy grid in terms of additional costs for BETs. However, it is crucial for the development of BETs that the grid infrastructure is also improved. Policy from the EC should therefore focus on its development to ensure that the sustainability of road freight transport is not held back by the energy network.

Finally, incentives can be created through communication and transparency. Transparency and effective communication between parties are pivotal in adopting new technologies. On the one hand, this communication consists of communicating the potential of BETs, especially in the future with the introduction of MegaWatt chargers. This will encourage transportation and oil and gas companies to invest in this alternative. Therefore, the development of the infrastructure is encouraged. Since investments are already being made in all three alternatives, using all three will not end just yet either. Thus, there is also an important component in properly deploying the alternatives. The results showed that if BETs cannot be driven in the future scenario, the best choice is hydrogen for distances between 750 to 3750 kilometres. It is not possible to force transport companies to drive only certain distances with a certain vehicle. However, it is possible to show the advantages over one another through education and communication, which can ultimately create support for adherence to the advice.

It is noticeable that the costs of the vehicles constitute a large portion of the total system costs. Therefore, this research has also contributed to the understanding, that, in addition to infrastructure, it is important for the costs of these trucks to decrease. This can be obtained by subsidising the purchase of the BETs for example. The results of the future scenarios show that even in the long term, the alternatives are still not economically competitive with diesel. So this calls for long-term policy and stimulation of alternatives in road freight transport, and not for short-term market stimulation.

Table 12.1 shows a summary of the discussed policies. The table includes the insights of the research and relates them to policy. In addition, the table describes the objective of the policy.

13

Conclusion

In the face of escalating environmental concerns and the ever-growing demand for efficient logistics, this research provides insight into the alternatives for fossil fuels within road freight transport. Previous research has focused on comparing alternatives and identifying the strengths and weaknesses of the alternatives individually. Therefore, the objective of this research is to combine alternatives for fossil fuels in road freight transport, and explore the system behaviour at a network level. This chapter answers the main research question:

> ”*How does combining Electric, Hydrogen, and Bio-LNG heavy-duty vehicles in road freight transport impact the costs and emissions in Europe while ensuring the reliability of the refuelling network, considering technological development, freight growth and limited supply?*”

To achieve this objective and answer the research question, this research started with an analysis of the current system, which involved a stakeholder analysis, system requirements, and an institutional analysis. It highlighted the importance of collaboration between the stakeholders and the need for regulation. Creating a more sustainable system for the future is complex due to the different incentives and requirements of the stakeholders within the system. The European Commission is identified as the problem owner. However, the EC doesn't have the tools to fully control the system. In addition, due to the high risk of sunk costs, the oil and gas companies and transport companies don't have an incentive without regulations to invest in sustainable alternatives. These insights highlighted the need for a better understanding of the system to achieve improvements in the collaboration between the stakeholders.

A reflection of the current system has shown that the use of diesel in the road freight network can not ensure meeting the system requirements. By the reliance on diesel the system fails to be sustainable. In addition, the system is facing future risk of fuel insufficiency, threatening system reliability.

Two metrics have been identified as system performance measurements: yearly cost and yearly CO_2 emissions. A freight simulation model and a location optimization model by K-means have provided insights into the system cost and emissions under different conditions. The system's performance is further understood by experimenting with the different drive range intervals and percentages of using the alternatives. To ensure the future robustness of the system, scenarios are formulated in which the technology development and freight growth are taken into account.

According to this research, with the development of the alternatives there will be a reduction of emissions by the use of the alternatives. As expected, using the alternatives (if green hydrogen is used) will, therefore, contribute to sustainable freight transport. The detailed analysis across various distance intervals reveals that, with further development, Battery Electric Trucks (BETs) will be the most cost-effective option across all ranges. Therefore, according to this research, the strategy of combining different alternatives based on specific distance ranges does not lead to cost reduction.

Bio-Liquefied Natural Gas (Bio-LNG) and Battery Electric Trucks (BETs) seem to be considerably promising as sustainable fuel alternatives. Bio-LNG stands out for its immediate viability, while BETs demonstrate potential in light of the expected technological developments. In contrast to Bio-LNG and BETs, the prospects for hydrogen as a sustainable alternative remain uncertain. In the absence of advancements in hydrogen technology and a scarcity of green hydrogen production, hydrogen causes high costs and surpasses diesel in terms of pollution. Consequently, if the progression of hydrogen technology stagnates or fails to meet expectations, the financial and environmental impact will be substantial. Therefore, investment in hydrogen carries inherent risks, underlining the need for careful and strategic consideration in the shift to hydrogen.

The Value of Time (VOT), and therefore, the penalty costs for refuelling time impact the system performance. Under the current conditions, an increase in the VOT, which may be due to the high value or perishable nature of the cargo, negatively impacts the feasibility of BETs for long-haul routes compared to hydrogen and Bio-LNG. The costs per kilometre for long-distance trips increase for BETs compared to hydrogen and Bio-LNG. The technological developments enable longer driving ranges and reduce charging times for BETs. Consequently, decreasing the impact of penalty costs on BETs' long-distance cost performance in future scenarios.

The results suggest that adopting a singular alternative fuel could be more cost-effective and environmentally friendly than combining alternatives for different drive ranges. Nevertheless, committing exclusively to one alternative carries risks, given the dependence of their technological development on the system's performance. The findings of this research highlight a promising potential for BETs. However, policy should not focus on banning other alternatives. Instead, the policy should focus on the robust deployment of BET infrastructure. This involves expanding the energy grid, offering conditional funding, standardizing MegaWatt charging stations, and clearly communicating the potential of the various alternatives to stakeholders. Additionally, given that vehicle costs contribute a significant proportion of the total system costs, the European Commission might consider incentivizing the purchase of sustainable trucks by subsidizing. These policies catalyse the shift towards a greener freight transport sector.

14

Discussion and Recommendations

This chapter delves into the interpretation of the findings presented in the previous chapters of the thesis. The overarching goal of this research is to understand the current system and further explore the system performance for combining different alternatives for freight transport in terms of costs and emissions. In this chapter, the implications of the findings and their relevance in a broader context are discussed. First, a summary of the results will be given. Then, the interpretations and how the findings relate to previous research will be discussed. Finally, the limitations and recommendations are provided.

The research findings indicate that combining alternative fuel options improves system emissions. However, combining alternatives doesn't decrease system costs compared to the use of a single alternative. Currently, using Bio-LNG would be beneficial in terms of cost and emissions. Also, when the effect of different distance ranges is considered, it can be concluded that Bio-LNG, considering the current technology, has the most potential. The difference in cost per kilometre between Bio-LNG and BETs is smallest at short-range ranges and increases as the distances increase at the ranges.

However, if the future scenarios are considered, the potential of BETs is notable. This alternative outperforms the other two alternatives at almost every distance range on both costs and emissions. If the future system is considered for the other two alternatives, hydrogen and Bio-LNG, it is more advantageous to drive with hydrogen in medium-long distances, between 500 and 3500 km. In doing so, it is very important that hydrogen will develop as included in the model, otherwise hydrogen is in no way competition for other alternatives.

The study is reasonable in line with previous research. This research builds upon existing literature but extends it by offering a more integrated analysis of the potential of combining different alternative fuels. This research considers various factors such as infrastructure requirements, costs, emissions, and technical limitations. The study aims to understand how different combinations of alternative fuels can impact the overall system and contribute to the transition towards sustainable freight transport. The results highlight further that hydrogen's potential may be lower than previously thought, especially if developments and production of green hydrogen lag behind. This makes investing in this alternative a big risk. This risk-averse and hesitant attitude is currently reflected in the market. However, if the expected developments take place, hydrogen will be able to be competitive with BETs and Bio-LNG in the future. Therefore, this research confirms with combining alternatives at the network level and previous research at the vehicle level.

In addition, the study also revealed new insights. The Bio-LNG alternative is currently seen mainly as an alternative for long distances, however, this research shows that currently the use of Bio-LNG is also a good alternative on short distances. In the future, the potential of this alternative decreases compared to BETs, and BETs will be a good alternative for both long and short distances. BETs are often seen as alternatives for short distances, but with the determined VOT, BETs also perform relatively well for long distances. Based on previous literature, it would be expected that the model would be more sensitive to the short-range and long-charging times of BETs.

14.1. Limitations and Further Research

Although this research has tried to give as complete a picture of the system as possible, limitations also exist in this study. The following section aims to discuss the limitations of this research transparently. After the research limitations and its impact have been discussed, some suggestions for future research in this field will be made.

The research limitations can be divided into more technical limitations of the model and socio-technical elements. First, the determination of costs. This research uses financial costs and time costs. Nonetheless, this perspective is somewhat restrictive, as it omits other cost dimensions, such as social costs, which encompass impacts on the community. Including the other types of costs in future research can provide a more complete picture of the total system costs and could provide more reflective of the social implications.

Secondly, truck flow was chosen to be included instead of freight weight. Therefore, the payload of vehicles is considered out of scope. The use of batteries affects the payload of trucks. Batteries are heavy, and when the battery has more capacity, the weight increases; thus, the vehicle's payload capacity decreases. Therefore, it is likely that when the payload is included in the model, the potential of BETs will decrease slightly, depending on battery developments. Future studies could incorporate the payload of the trucks into the model. This would provide insights into how the weight of batteries in electric trucks affects their payload capacity and the system's overall efficiency.

Well to Wheel CO_2 emissions were used in this study to determine environmental impact. This gives a comprehensive view of fuel emissions because transport and production of the fuel are also included in this analysis. However, some particulates that are not included in this analysis affect the environment. Bio-LNG may have low CO2 emissions but requires land and water use and, therefore, causes an environmental impact that is not considered in the model. Moreover, emissions generated from truck production are not included in this research. The production of batteries uses non-renewable resources, like lithium or cobalt. This may affect the overall performance of this alternative especially for BETs. Future research could focus on these further environmental impacts on the system as well.

In addition, the data. The model uses freight data. In this data, a growth factor is used to predict the future. This assumes that freight can grow infinitely and does so according to a trend. However, that is not very realistic. There is also the perspective within the EC in which the use of rail should be stimulated. Rail is a good alternative to the road. However, the current rail capacity is insufficient to accommodate the switch to rail. Nevertheless, it could be that the growth of freight is less than expected. Thus, it is questionable whether the 2040 forecast used in this study is realistic. On the other hand, it does show how the model, and thus costs and emissions, respond to changes in freight demand. This can still be seen as relevant.

Due to time constraints, input variables were not tested for sensitivity within the model. In subsequent research, it is valuable to do so. This would also allow to investigate which technical elements (charging time, drive range or energy consumption) are most relevant to improve in order to improve the overall performance of the system. This could stimulate truck manufactures to design improvements of trucks efficient.

The model creates three new data sets based on the complete data set. Based on this, a network of refuelling/charging stations is established for each alternative individually, after which the costs and emissions are determined individually for each alternative. By summing up these together, the total system costs and emissions are determined. This does not consider that a tank/charging station could also be combined for different alternatives. In reality a refuelling station could be suitable for both BETs and Bio-LNG when the optimal locations of these stations are close to each other. The effect of this is likely that the system costs decrease.

Truck drivers must take a mandatory 45-minute break every 4.5 hours [71]. These breaks are not accounted for in the model. The truck could be recharging or refuelling during this mandatory stop is required. If the charging fits within the 45-minute window and a vehicle does not need to refuel more often than every 4.5 hours, it be deducted from the penalty time. The effect on the outcomes would be that the penalty costs could likely be disregarded, especially for Hydrogen and Bio-LNG. For BETs, this is not currently the case, but with the technological development of MegaWatt chargers, the charging would fall within 45 minutes. Considering the rest time in future research would provide a more realistic perspective on the alternatives.

The last limitation is the difference in perspectives on the use of alternatives between European Union member states. Besides freight growth, this study does not include the difference between member states in perspectives. Member states differ in economic development and, therefore, in how different alternatives are considered. In some countries, sustainability is higher on the political agenda, or the budgets for its realization are higher. As a result, the preference for a particular alternative may differ from country to country. Although this study approaches the problem from a European perspective and the EC has certain tools to influence the system, the member states and their support are just as important. Future research could focus on analysing economic, political, and social factors influencing the adoption of different technologies. This would ensure meeting requirement 3.3, which is in this study limited guaranteed.

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A

System Description Analysis

This appendix includes the analysis used for the system description.

A.1. Stakeholder Analysis

A stakeholder analysis analyses the different stakeholders in the field. Understanding the stakeholders and their objectives, values, and power helps design a system that fits the context. First, an extensive list of stakeholders has been made, including a short description. Thereafter, these stakeholders are placed in a power interest grid to identify which stakeholders have a crucial role in this socio-technical system.

A.1.1. Identification of stakeholders

European Commission (EC): The EC helps to shape the European Union's (EU) overall strategy. The Commission manages the EU budget and proposes new EU laws and policies. In addition, the EC is responsible for implementing the laws and policies [18]. Due to these features, the EC has the tools to make changes to the system's current state. Therefore, The Commission can be seen as the problem owner.

Emissions aren't limited to country borders. Therefore, the European Commission has set an objective: by 2050, transport emissions will have to be reduced by 90%, compared to the levels of 1990. The roll-out of a sufficiently dense, widespread network of alternative fuels infrastructure is critical to this transition to low- and zero-emission alternative fuels [14]. This objective results in a very high interest of this stakeholder. In addition, by creating policies and laws, the EC's power can be considered high.

Part of the EC is the European Alternative Fuel Observatory (EAFO). They are a technology-neutral organization and are there to be the bridge between the industry and the EC or local governments. They provide information and relevant data for the different parties. As they are a technology-neutral organization, they don't prefer one of the alternatives over the other.

National Governments: The national government of the member states of the EU have sovereignty. However, EU law is superior to national law, and national laws must be consistent with EU law. The national government of member states play a significant role in implementing and enforcing EU law. Therefore, the role of the national government is prominent in the transition towards alternative fuels.

Oil and gas producers: Traditionally, oil and gas companies are associated with fossil fuels. Nevertheless, they play a pivotal role in the transition to alternative fuels. Many oil and gas companies are diversifying their portfolios, investing in and facilitating refuelling infrastructure development for sustainable alternatives.

Their power can be considered as high. Oil and gas companies wield significant economic and infrastructural power. Their investments in infrastructure give them influence in shaping the transition to alternative fuels. The interest may vary among companies. However, due to increasingly stringent regulations on emissions and the use of fossil fuels, interest is rising for these companies. The policies on the European level being put in place will affect the path these companies will take.

Transport companies (including fleet operators): The transport companies are at the forefront of the shift towards sustainable alternatives. They determine the choice of vehicles and fuels used in their operations. The transition to alternative fuels requires a strategic shift in their fleets. The commitment of transport companies to invest in and operate vehicles running on alternative fuels is essential for the success of the overall transition.

The power of the transport companies can be considered as high to moderate. Transport companies influence in shaping the market for road freight transport. The decisions on fleet composition and fuel choices can drive demand for sustainable alternatives. The interest is in transport companies. Transport companies are increasingly interested in adopting sustainable alternatives. Choices in policy can affect transport companies' business significantly.

Investors: Currently, the industry is investing in a sustainable industry. The awareness and the urgency of this transition are increasing. However, external investors can additionally speed up this transition. Their investments can help to unlock opportunities and drive innovations. Therefore, external investors can accelerate the adoption of sustainable alternatives in the road transport sector.

Customers: The customers drive demand for sustainable road freight transport. As the awareness of environmental issues grows, there is an increasing preference for businesses that prioritize eco-friendly transportation methods. Their choices can create an extra market pull for cleaner transport options, encouraging the industry to invest further in sustainable solutions. However, their preference relates a lot to the cost. Customers, in general, want the lowest cost. Creating a more sustainable sector requires extra costs. This results in their power and interest being relatively low.

Vehicle Manufactures: The vehicle manufacturers produce and supply the trucks that run on alternative fuels. By investing in research and development, these manufacturers can accelerate the production of the trucks. However, the type of vehicles that will be produced mainly depends on the market demand. If the demand increases for the trucks that run on alternative fuels, the production will increase as well, since the manufacturers are profit-driven. Therefore, the power and interest of this stakeholder can be considered relatively low.

A.1.2. Interview EAFO

Date: 2-11-2023
Attending: Mate Csukas (EAFO) and László Kerényi (EAFO)

During the interview, both parties gave a brief presentation after which there was time to ask a few more questions.

What is the role of the EAFO? The EAFO consist of several people from companies involved in making the transportation sector more sustainable. The EAFO is a link between the European Commission and the industry. The EAFO is mainly responsible for providing data on alternatives to fossil fuels and policies for the entire transport sector (not just roads).

What tools does the EAFO have to influence the system? The EAFO influences the system mainly by providing information to the sectors. When, at the national or European level, changes are made regarding regulations, the EAFO communicates that towards the sector. But they also communicate about refuelling/charging infrastructure.

What is the perspective of the EAFO on the different alternatives? The EAFO is a technology-neutral organisation. So, there is no preference from the EAFO for any of the alternatives. They are trying to jump in where the market demands. Currently, they do notice that the market is moving more and more toward BETs. As a result, they are also further developing this alternative's information provision.

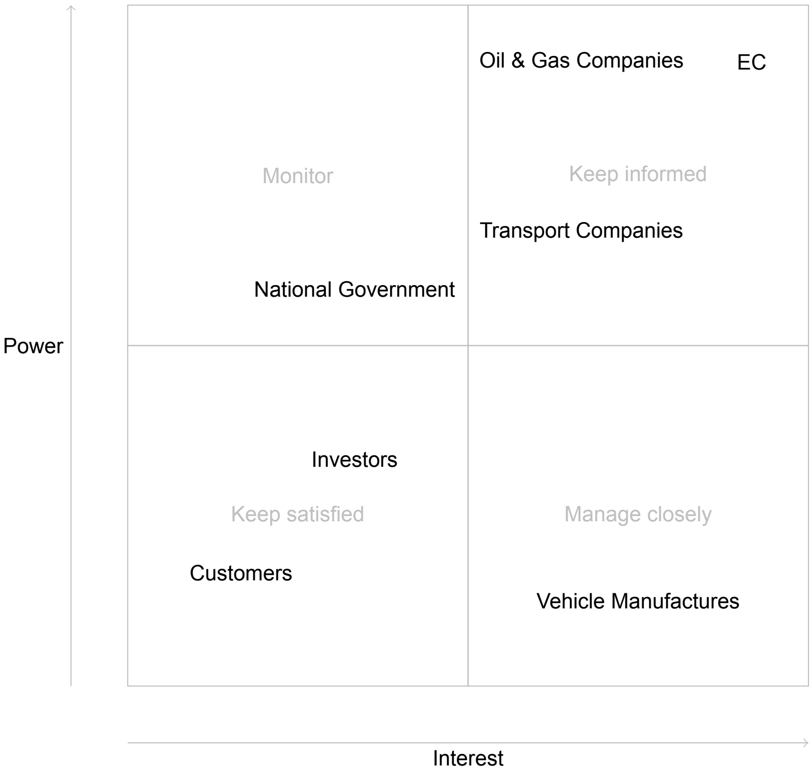

Figure A.1: Power-Interest Grid

What is more important, system cost or system emissions? This is a very political question, and therefore, the AEFO can't answer it. Again, it was mentioned that they are a technology-neutral organization. But this choice depends on different member states and the industry.

A.1.3. Power Interest Grid

The stakeholder landscape has been placed into a power interest grid; see figure A.1. This visualisation provides insight into the importance of the stakeholders. The stakeholders, placed in the upper right quarter (European Commission, Transport companies, and Oil and Gas Companies) can be seen as stakeholders that must manage closely. Therefore, these stakeholders are the key stakeholders of the system.

In addition, the European Commission can be seen as the problem owner. It is one of the main stakeholders with a high interest and power. The European Commission is saddled with limiting global warming from a European perspective. In doing so, the European Commission can make regulations requiring member states and other stakeholders to participate in the transition. As a problem owner, the European Commission thus can turn knobs and thereby oblige other key stakeholders to cooperate with the plans. However, carefully weighing these considerations is important to get the support and cooperation of other key stakeholders.

A.2. Technical Analysis

To make the network design useful, it is essential to consider the requirements of the key stakeholders. By considering these, you increase the likelihood that the design/model will meet the stakeholder's needs, allowing it to be considered and implemented. Otherwise, you run the risk of designing something that is not a solution to the actual problem. For each key stakeholder, the main values that are related to the issue are identified in table A.1

As can be seen in table A.1 there is overlap between the values of different stakeholders. In addition, some of the values will have the same outcome. For example, cost-effectiveness and profitability. The probability of getting a profitable business case increases if the project is cost-efficient. Based on the

Table A.1: Values of key stakeholders

Stakeholder	Identified value	Explanation	Sources
European Commission	Reliability	A reliable refuelling station network is essential for the smooth operation of road freight transport. Delays in transport due to fuel shortages or station closures can increase transportation costs and, therefore, the prices of goods. A reliable network supports the EU's economic stability and competitiveness.	[20]
	Accessibility	An accessible refuelling station network is essential for the efficient functioning of the road freight transport sector. This, in turn, enhances the overall competitiveness of the European economy, which is crucial for business and trade within the EU.	
	Cost-effectiveness	To be economically competitive, having a cost-effective road network is important.	
	Sustainability	One of the aims of the EC is to protect and improve the quality of the environment. Therefore, the European Commission has, in this context, the sustainability value.	
Oil and Gas Companies	Profitability	For Oil and gas companies, profitability is crucial for the financial sustainability of any organization	[31]
	Efficiency	Efficiency ensures that the organization optimally utilizes its resources. Therefore, efficiency can lead to cost reduction. This can make renewable energy more competitive with conventional fuels.	
	Scalability	Scalability can lead to economies of scale, which can lead to cost reductions. As the network grows, the fixed costs can be spread over a larger customer base.	
Transport companies	Sustainability	To make transport future-proof, it is important to invest in sustainability and the environment. If the transport companies don't invest in sustainability on time, they could face high costs later.	[32]
	Accessibility	Accessibility is an important value for transport companies to deliver the goods on time.	
	Affordability	The system should stay affordable. If the costs rise, the transport companies will reflect that in the price. Therefore, the overall price which should be paid by the consumer will increase, which is not desirable.	
	Reliability	For transport companies it is important that the system is reliable. Reliability means that there is enough fuel and enough stations for transport companies. If the supply of the fuel is insufficient, there is a risk of not being able to operate, which can cause high losses.	
	Safety	Safety relates to the safety of the employees and the surroundings. Besides this, the system isn't safe, and accidents happen, which can result in a bad image for the transport companies, which results in profit losses.	

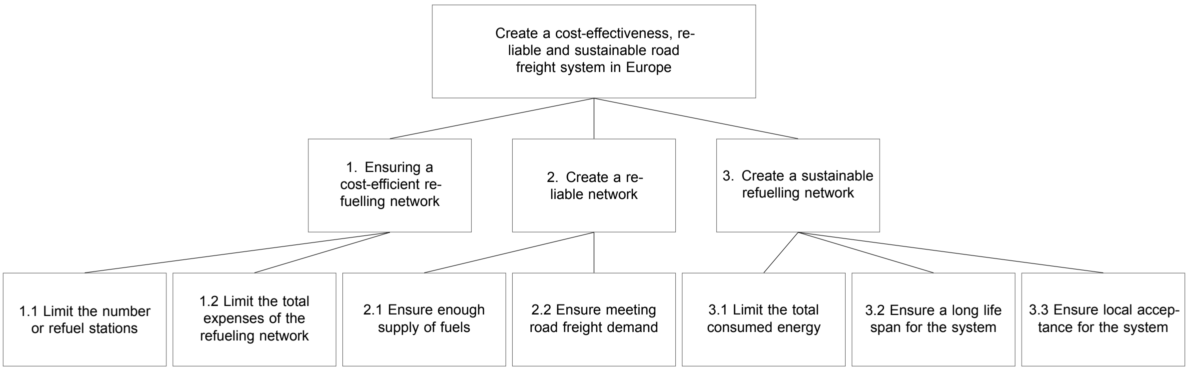

Figure A.2: Requirement structure

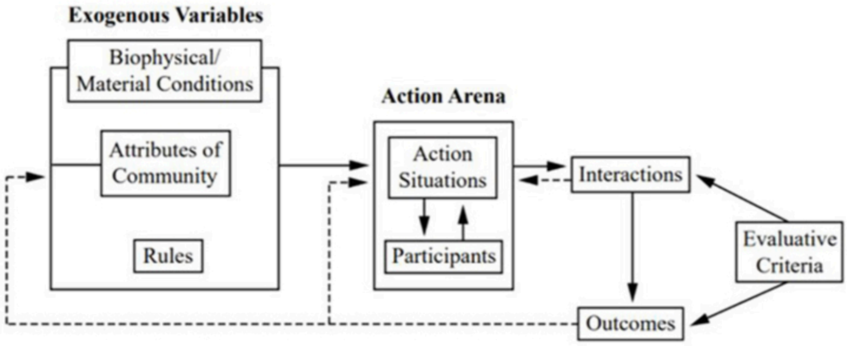

Figure A.3: IAD framework [47]

values of the key stakeholders, a value-based mission statement can be identified: ”*Create a cost-effectiveness, reliable and sustainable road freight system in Europe*”

A.3. Institutional Analysis (IAD framework)

The IAD framework [47], which can be found in figure A.3, is a theoretical framework that is used to study and understand the interactions within a system in various contexts.

Exogenous Variables :

- *Biophysical/Material Conditions:* In this context, multiple biophysical/material conditions can be identified. One of them is the infrastructure development. The availability of resources and, therefore, the availability of sustainable alternative fuels. Not all the alternatives are currently available in an unlimited quantity.
- *Attributes of Community:* The European road freight transport community’s characteristics include its size, diversity, and economic interests. Freight transport comprises a large number of companies, and it employs a large number of people. The European road freight transport sector is highly diverse.

  In addition, the attributes of the community also include relevant aspects of the social and cultural context. This includes attitudes towards sustainability. Climate change and sustainability are becoming more prominent in society, which is why there are protests to draw more attention to this issue. It is a sensitive and complicated topic. It also means that societal decision-making affects more than just the transportation sector.
- *Rules:* Existing regulations and policies related to the transportation and energy sectors in Europe, including environmental regulations and trade agreements. The Paris Agreement, European Climate law, and regulation for the deployment of alternative fuel infrastructure

are examples of current rules that apply to the system.

Action Arena :

- *Action situations:* The action situation can be defined as decisions and actions regarding the rollout of a sustainable road freight network. This includes the creation of a new refuelling station network.
- *Participants:* First, the European Commission has the ability to form policies and regulations to accelerate the transition toward an alternative refuelling road network for freight transport. Secondly, the oil and gas companies need to invest in the new infrastructure to meet the policies and regulations of the EC. Finally, the transport companies have to make investments as well. For example, the vehicles that will be used will result in a particular fuel demand.

Interactions: The interactions between stakeholders in the Action Area involve negotiation, cooperation, and competition. The European Commission may seek to establish regulations and incentives for sustainable fuel adoption. Oil & Gas Producers may lobby for their interests. Between the oil and gas producers, there is competition, which influences their decisions and incentives. The transport companies may advocate for the needs of the transport industry. These interactions are influenced by the rules and regulations in place.

Outcomes: The outcomes of these interactions could include the development of a sustainable refuelling station network, changes in regulations and policies, investment in research and development of alternative fuels, and shifts in market dynamics.

Evaluation Criteria: Evaluation criteria for the outcomes are environmental sustainability and consumed energy. In addition, cost, reliability, and acceptance are evaluation criteria.

In conclusion, stakeholder interaction is about balancing cooperation, negotiation, and competition. The outcomes, whether they lead to the realization of an alternative refuelling network for sustainable fuels or not, will be influenced by the alignment of their interests and strategies. T

Currently, both sides of the market, the oil and gas producers and transport companies, are hesitant to invest in sustainable alternatives. But both sides of the market need each other for the success of the other. Therefore, we can identify a chicken and egg problem within this system. The EC has a crucial role in this problem, where it has to bring an incentive to other stakeholders by subsidizing policies or regulations to realize a reduction of emissions.

B

Model Specification

B.1. Freight Data

The model uses European freight data of Speth et al. [59]. To create a better understanding of the data the descriptive analysis has been performed in SPSS for the freight data set. The table below shows the results. The data contains 1514573 origin-destination combinations, with an average distance of 1559 kilometres. Furthermore, the distance that occurs the most in the data set is 1271. As can be seen in figure 7.1 the data is right-skewed distributed, the tail on the right side of the histogram is longer than the tail on the left side, and the mass of the distribution is concentrated on the left of the figure. The minimum distance between an origin and destination is 8 kilometres, the maximum distance is 18234 kilometres.

Table B.1: Descriptive Analysis Distance

N	1514573
Mean	1559.693
Median	1271
Minimum	8
Maximum	18234

B.1.1. Causal relationship diagram

The causal relationship diagram in figure B.1 identifies the factors that affect the system. The model is used to visualize how different variables in the system are interrelated. The system metrics are shown in red on the right side of the figure. The model's parameters can be found on the left side in green.

The system metrics cost and emissions are influenced by factors in the system. First costs. The cost increases if the number of stations increases; building and operating stations costs money. The same applies to the operation and purchasing of vehicles. In addition, an increase in fuel production costs money and causes emissions. Furthermore, the emissions increase if the emission by the vehicle increases.

In green the system parameters are shown. An increase in the use of an alternative results in an increase in trips; therefore, more kilometres are driven, and the number of vehicles is increased, causing more emissions. If the kilometre range interval is increased, the number of trips also increases.

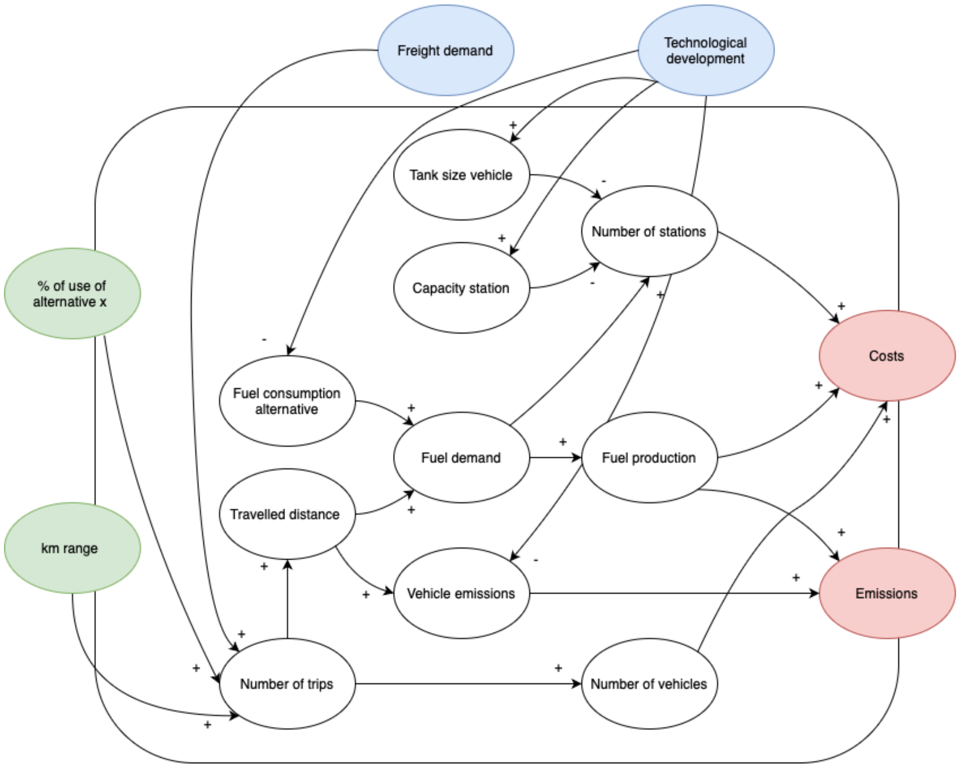

Figure B.1: Causal relationship diagram

B.2. Input variables

The model uses different input variables: Global input variables and alternative input variables. Previous research or other reliable resources are used to determine the value of the input variables.

Table B.2: Global input variables

Variable	Value	Unit	Source
Vehicle use	13.4	Years	[60]
Station use	20	Years	
Truck weight	36	Tonnes	[26]
Station maintenance	2% of capital cost	Euro/year	[28]
Cost index transport	0.0045	Euro/km	[69]
Cost index storage	2.69	Euro/kWh	[69]
Cost grid extension	0.5	Euro/kWh	[44]

Table B.3: Diesel input variables

Variable	Value	Unit	Source
Energy density	9.7	kWh/L	[10]
Fuel per km	2.74	kWh/km	[24]
Tank Capacity	250	L	[68]
Capital cost station	8800000	Euro	[40]
Fuel production cost	0.89	Euro/L	[27]
Vehicle cost	108500	Euro	[39]
WtW emissions	320	CO2/kWh	[24]

Table B.4: BET input variables

Variable	Value	Unit	Source
Fuel per km	1.53	kWh/km	[24]
Charging power	350	kW	[55]
Battery capacity	400	kWh	[55]
Capital cost station	72000	Euro/charger	[5]
Fuel production cost	0.053	Euro/kWh	[5]
Vehicle cost	277000	Euro	[62]
WtW emissions	134	CO2/kWh	[24]

B.3. Cost Equations

$$TC_{\text{production}_x} = C_{fuelproduction_x} \cdot c_{total_x} \quad \text{where,} \tag{B.1}$$

$TC_{\text{production}_x}$: Total costs for production of alternative x
$C_{\text{fuelproduction}_x}$: Production cost per unit of alternative x
c_{total_x}: Total energy consumption of alternative x in kWh

$$TC_{station_x} = \frac{(C_{station_x} \cdot K_x)}{t_{station}} + (C_{maintenance_x} \cdot K_x) \quad \text{where,} \tag{B.2}$$

$TC_{station_x}$: Total station costs for alternative x
$C_{station_x}$: Station capital cost for alternative x
K_x: Number of stations for alternative x
$t_{station}$: Time of use station
$C_{maintenance_x}$: Yearly maintenance cost for alternative x

$$C_{maintenance_x} = 0.2 \cdot C_{station_x} \quad \text{where,} \tag{B.3}$$

$C_{maintenance_x}$: Yearly maintenance cost for alternative x
$C_{station_x}$: Station capital cost for alternative x

Table B.5: Hydrogen input variables

Variable	Value	Unit	Source
Energy density	32.702	kWh/kg	[29]
Fuel per km	2.93	kWh/km	[24]
Charging time	1/3	Hour	[8]
Tank Capacity	1330	L	[39]
Capital cost station	3100000	Euro	[54]
Fuel production cost	3.8	Euro/kg	[61]
Vehicle cost	265500	Euro	[8]
WtW emissions	384	CO2/kWh	[24]

Table B.6: Bio-LNG input variables

Variable	Value	Unit	Source
Energy density	14.7	kWh/L	[7]
Fuel per km	2.74	kWh/km	[24]
Charging time	1/4	Hour	[72]
Tank Capacity	155	L	[38]
Capital cost station	1140000	Euro	[54]
Fuel production cost	0.325	Euro/L	[11]
Vehicle cost	128100	Euro	[58]
WtW emissions	32	CO2/kWh	[24]

$$TC_{vehicle_x} = \frac{C_{vehicle_x}}{t_{vehicle}} \cdot \frac{T_x \cdot N_{vehicles}}{T} \quad \text{where,} \tag{B.4}$$

$TC_{vehicle_x}$: Total vehicle costs for alternative x

$C_{vehicle_x}$: Vehicle cost

$t_{vehicle}$: Vehicle use years

T_x: Total number of trips for alternative x

$N_{vehicles}$: Number of vehicles

T: Total number of trips in system

$$T = \sum_x T_x \quad \text{where,} \tag{B.5}$$

T: Total number of trips in system

T_x: Total number of trips in with alternative x

Equation B.6 is determined according to Wang et al. [69]. This equation is used to calculate transport and storage costs for the transport of hydrogen and Bio-LNG by truck.

$$TC_{transport_x} = \sum_{i,j}(A \cdot d_{ij} + B) \cdot C_x \quad \text{where,} \tag{B.6}$$

$TC_{transport}$: Total transport costs for alternative x
C_x: Capacity of station alternative x
A_x: Cost index transport of alternative x
$d_{i,j}$: Distance between fuel plant i and refuelling station j
B_x: Cost index storage of alternative x

$$[Euro] = \sum([Euro/km] \cdot [km] + [Euro/kWh]) * [kWh]$$

Equation B.7 is used to determine the cost of grid connection and extension for BET refuelling stations.

$$TC_{transport_{BET}} = C_{grid} * c_{total_x} \quad \text{where,} \tag{B.7}$$

C_{grid}: Costs for grid extension per kWh
c_{total_x}: Total energy consumption of alternative x in kWh

C

Scenarios and Experiments

A system must be future-proof. However, it is not possible to predict the future. However, it is possible to use scenario analysis to see how a system behaves in different scenarios. To identify scenarios, external factors that could affect the system were examined. Table C.1 shows the different factors. It indicates which factors have a high probability of occurring and which factors will greatly impact the system.

Table C.1: External factors

External factor	Impact	Uncertainty
Technological development	High	High
Economic development	High	High
Availability of renewable fuels	High	High
Pandemic	High	Low
Raising oil and gas prices	Low	Low
War	High	Low

Table C.1 shows that two external factors have a high probability of happening and could have a high impact on the system. Based on these factors, different scenarios are identified; see table C.2.

The external effects and their impact on the system are shown in figure B.1. The figue shows that an increase in freight demand results in more trips between origin and destinations. In addition, an increase in technological development impacts the system with different factors. First of all, the fuel consumption of the alternative decreases; the vehicle uses less fuel per kilometre because it drives more efficiently. Second, it affects the emissions of the vehicle. In addition, technological development could influence the tank/battery size of the vehicle. Lastly, the developments could also increase the capacity of a station due to shorter charging/refuelling time. The effect of the technological developments differs per alternatives.

Table C.2: Identification of scenarios

Freight	Technological	Availability	ID
No growth	No development	Infinite	1
		Limited	2
	Development	Infinite	3
		Limited	4
Growth	No development	Infinite	5
		Limited	6
	Development	Infinite	7
		Limited	8

As a result of this analysis, the input variables of the model are adjusted according to table C.3.

Table C.3: Adjustment of input for scenarios

Variable	Standard value	New value	Source
BET fuel use	1.53	1.44	[5]
Battery capacity	400	800	[37]
Charging power	350	1200	[41]
BET WtW	134	37	[23]
Hydrogen fuel use	2.93	2	[25]
Hydrogen production cost	3.8	1.9	[2]
Hydrogen WtW	384	36	[23]
Freight demand	2019	2040	

C.1. Experiments

After identifying the scenarios, experiments were conducted to investigate the model's behaviour under different parameters. This section in the appendix provides the input for the four experiments performed to understand the system's behaviour.

C.1.1. Individually testing

First, the model has determined the cost and emissions for each alternative individually to create a better understanding of each of the alternatives. Therefore, the input variables are used as described in table C.4. The model is run for each of the alternatives individually; the input parameters for this experiment ensure that all trips are assigned to one of the alternatives. If, for example, BETs are examined, the parameters of the other alternatives are set to 0.

Table C.4: Parameters Experiments individually testing

Alternative test	Parameter	Value
BET	a	U(0, 7000)
	b	U(a, 18234)
	EV1	1
	EV2	1
	EV3	1
	Other parameters	0
Hydrogen	a	U(0, 7000)
	b	U(a, 18234)
	H1	1
	H2	1
	H3	1
	Other parameters	0
Bio-LNG	a	U(0, 7000)
	b	U(a, 18234)
	LNG1	1
	LNG2	1
	LNG3	1
	Other parameters	0

C.1.2. Ranges

In the following experiments, the ranges of the alternatives are adjusted. The data is assigned to all alternatives according to table C.5. In the first experiment, all trips with a distance between 0 and 250 kilometres are assigned to BETs, Hydrogen and Bio-LNG individually. Ranges larger than 5000 were not included in this experiment because there are not enough trips in the dataset to create a solid network. In the results, the costs per kilometre are compared between these alternatives over the distance.

Table C.5: Distance of range intervals

Distance interval (in km)	
From	**to**
0	250
250	500
500	1000
1000	1500
1500	2000
2000	2500
2500	3000
3000	3500
3500	4000
4000	4500
4500	5000

C.1.3. Availability of alternatives

As described earlier, not all alternatives are available in unlimited quantities. Table C.6 shows the used values for availability.

Table C.6: Availability of fuels

Alternative	Value
BETs	Unlimited
Hydrogen	20Mt
Bio-LNG	585 TWh

C.1.4. VOT sensitivity

The last set of experiments examined the model's sensitivity to the VOT. The value was increased relatively highly to determine the effect of this VOT. Therefore, it was increased by 50%. A higher VOT may depend on the type of goods being transported or the location they are being transported to. The initial and new value is shown in table C.7.

Table C.7: VOT Experiments input

Experiment	VOT
Standard	3.1015
+50%	4.65225

D
Results

Appendix D presents the results supporting this thesis's primary purpose. The appendix is structured to align closely with the chapters of the thesis.

D.1. Alternative system performance

First, the various alternatives were compared individually against each other based on the resulting system's costs and emissions.

D.1.1. Emissions

Figure D.1 and D.2 show the emissions with the current state of technology and expected technological development.

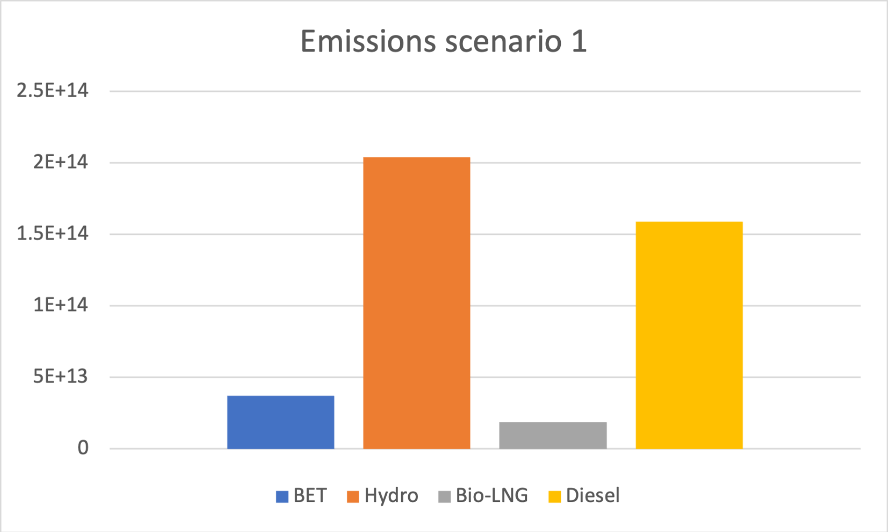

Figure D.1: Emissions alternatives scenario 1

Currently, the emissions of hydrogen are very high due to the use of grey hydrogen. In addition, with the current European electricity mix, bio-LNG would be the most sustainable.

When considering future developments, it is noticeable that all alternatives perform better than Diesel trucks. BETs have the lowest emissions in this scenario.

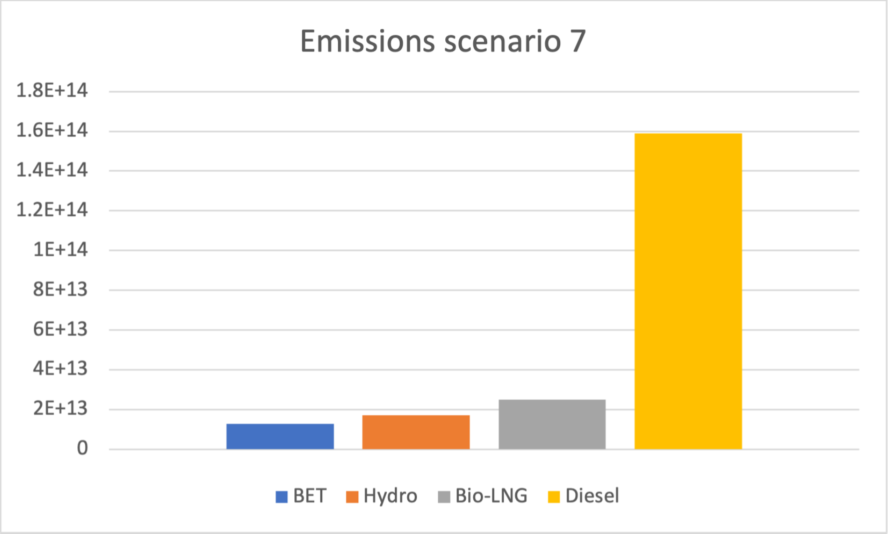

Figure D.2: Emissions alternatives scenario 7

D.1.2. Costs

Because a complete diesel network is already in place, comparing the costs of the alternatives to diesel is impossible. In the current situation, after diesel, Bio-LNG is the cheapest, then BETs, and hydrogen is the most expensive relative to the other alternatives.

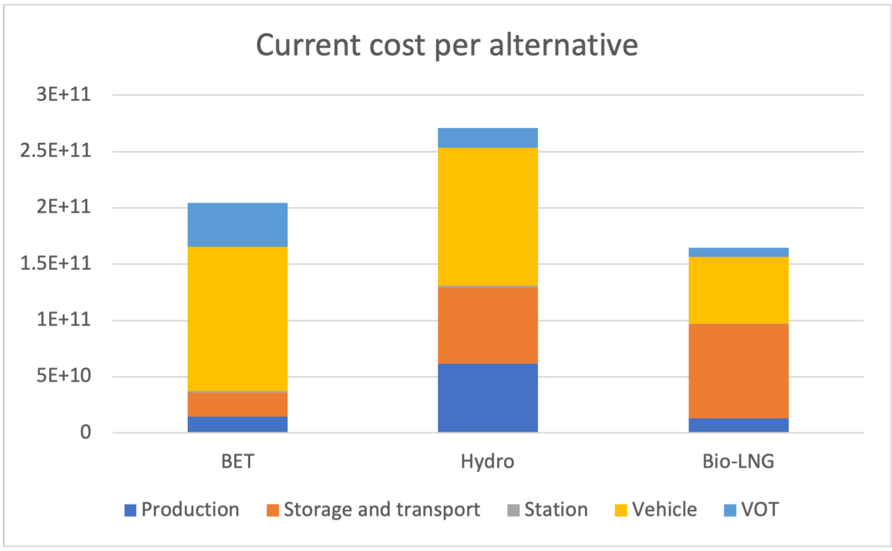

Figure D.3: Costs proportions scenario 1

In the future scenario, the ratios between the alternatives change. In this scenario, diesel remains the cheapest (not shown in the figure). The position of BET and Bio-LNG is reversed from scenario 1. Hydrogen also remains the most expensive in this scenario. In both scenarios, much of the cost is spent on vehicles. In addition, the relative proportion of the production cost decreases if scenarios 1 to 7 are compared.

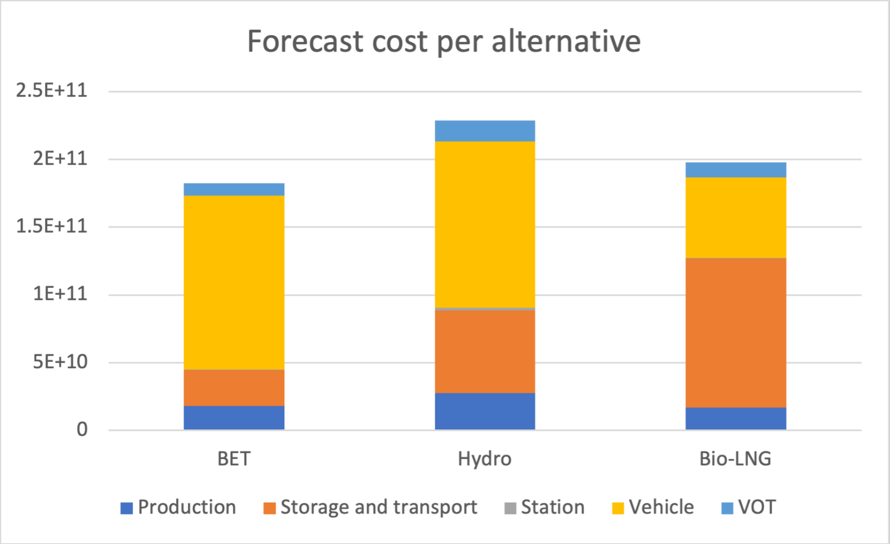

Figure D.4: Costs proportions scenario 7

D.2. Ranges

The alternatives were also compared for different distance intervals. These experiments attempted to gain insight into how alternatives perform at different distances. By comparing the alternatives at different distances, finding favourable travel distances for each alternative is possible.

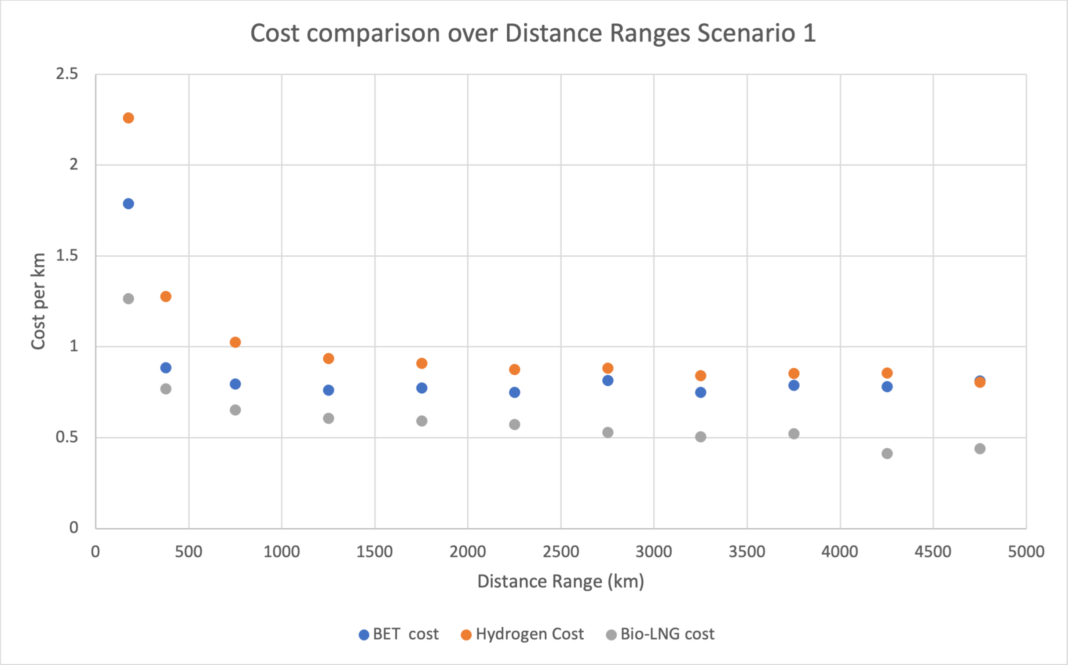

Figure D.5: Distance range scenario 1

Results for Scenario 1 show that Bio-LNG is the cheapest alternative at any distance because it offers the lowest cost per kilometre, followed by BETs; hydrogen is the most expensive alternative. Thus, these results match the pattern shown in figure D.3. For scenario 1, it is not beneficial to combine alternatives compared to the single use of one of the alternatives because there are no changes in order of price over the distances.

For scenario 7, BETs show potential. At almost every distance, BETs perform the best. The further the

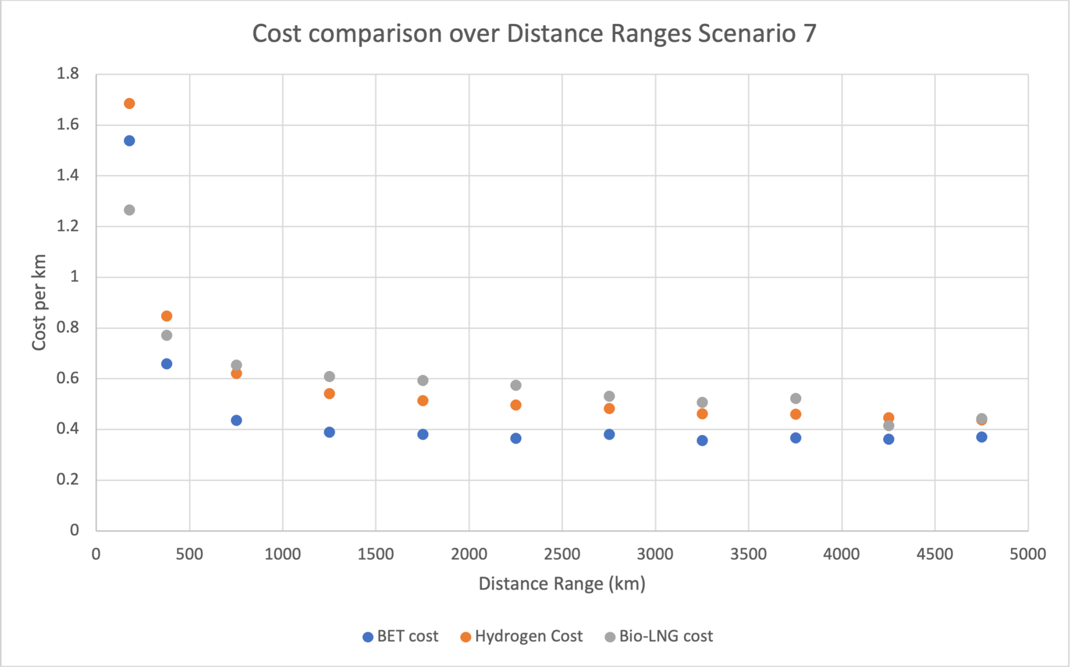

Figure D.6: Distance range scenario 7

range interval is, the closer the cost of the alternatives is to each other. For retrieving this result for the system, technological development is essential. The potential of BETs relies mainly on bigger battery capacity and shorter recharging times.

Figure D.4 shows that the cost of hydrogen is the highest. However, the results in D.6 show that hydrogen is cheaper for distances between 500km and 4000km than Bio-LNG. Due to the high number of trips of the shorter distances, the overall cost for hydrogen seems to be higher than Bio-LNG in figure D.4.

D.3. Monte Carlo Simulation

The Monte Carlo simulation further explored the solution space and highlighted the differences between the scenarios. In addition, the Monte Carlo Simulation shows that the results of the different range intervals, in appendix D.2, also apply when the model uses random values and the alternatives are combined.

In the Monte Carlo simulation, random values are generated for the values of A and B with a uniform distribution: 0 - A km, A km - B km, and from B km - max distance. In addition, also the value for the percentage of which alternative is used is determined randomly by a uniform distribution, see figure 7.2. This method ensures assigning all trips to one of the alternatives.

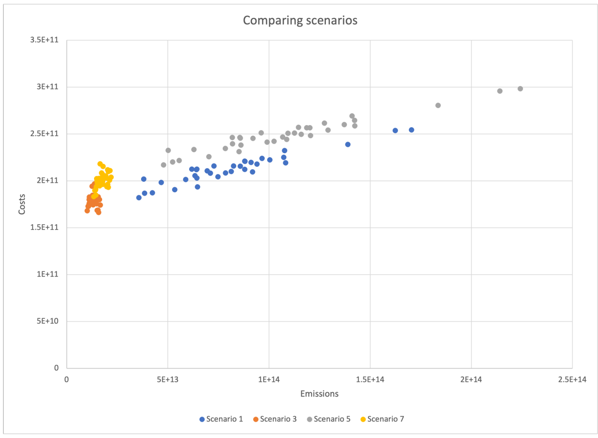

Figure D.7: Hypothesis comparing

Figure D.7 shows the performance of the runs in different scenarios relative to each other. In particular, technological development greatly affects the performance of the alternatives. The developments reduce costs and emissions.

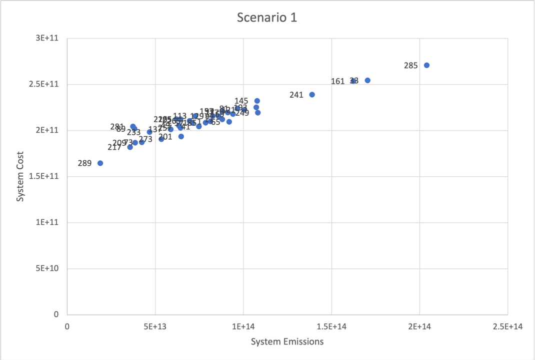

Figure D.8: Results scenario 1

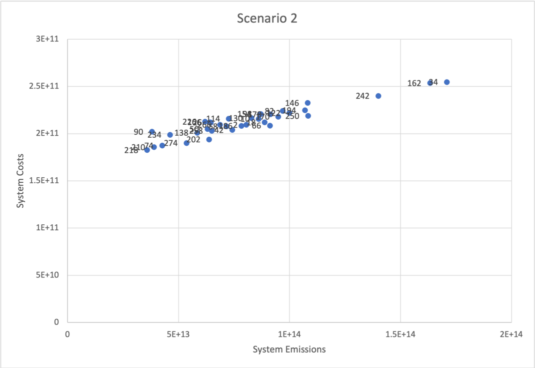

Figure D.9: Results scenario 2

The growth of freight only shifts the results up the graph. Furthermore, the limited availability of alternatives has little effect on the system when combining alternatives. There is sometimes an insufficient amount of bio-LNG available, causing the model to choose a new value, thus adjusting the solution space.

The model shows no surprising behaviour from previous results. Therefore, the Monte Carlo Simulation confirms the previous results, and no new conclusions can be drawn from this simulation. Therefore, this simulation is not further mentioned in the main text.

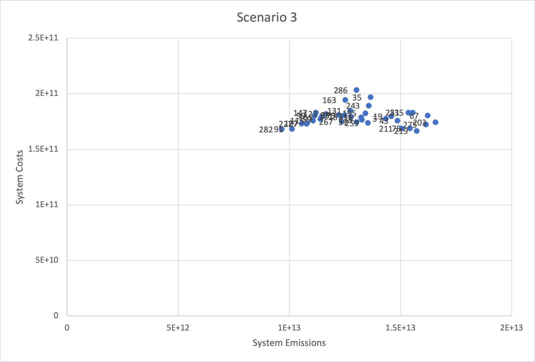

Figure D.10: Results scenario 3

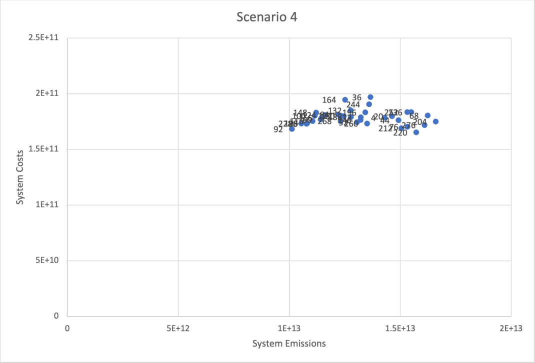

Figure D.11: Results scenario 4

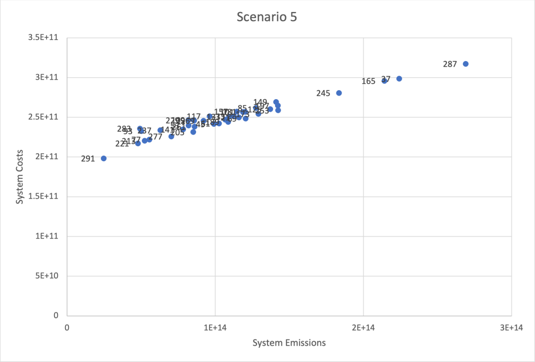

Figure D.12: Results scenario 5

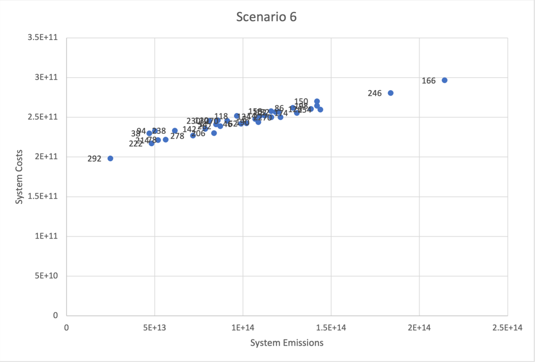

Figure D.13: Results scenario 6

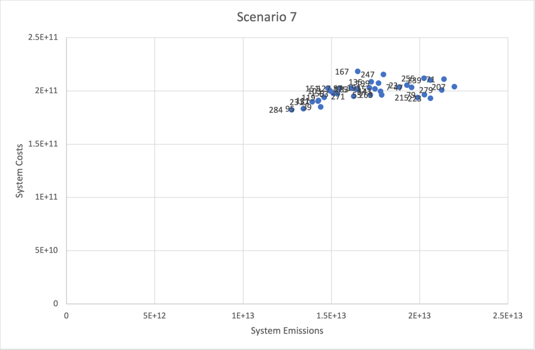

Figure D.14: Results scenario 7

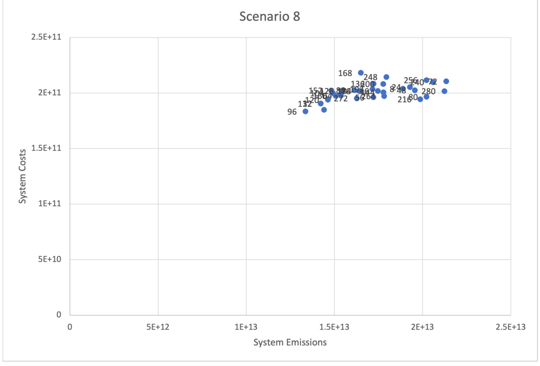

Figure D.15: Results scenario 8

D.4. Availability of alternatives

The simulations in appendix D.3 show the performance for the different scenarios. In addition, it takes into account the limited availability of green hydrogen and Bio-LNG. To create a better understanding of this limitation, the model determines the fuel demand for the different ranges.

If the green hydrogen supply is scaled up to the expected 20Mt, there would be enough green hydrogen to supply the road freight transport sector fully. Therefore, the hydrogen supply would not be a limitation to the system.

According to this research, there would not be enough Bio-LNG to supply the system entirely. This creates a risk for relying on Bio-LNG; there may be insufficient fuel to ensure a reliable network. Therefore, based on previous results, it can be concluded that especially longer distances could be driven with Bio-LNG because the financial advantage over the alternatives is the greatest. This applies to both scenarios.

Range	Hydro kWh	Bio-LNG kWh
125	1.14751E+11	1.85896E+11
375	85955150180	1.39247E+11
750	69550680416	1.32672E+11
1250	44877247334	72701140680
1750	22896183794	37091817746
2250	13683806165	22167765988
2750	5175133941	8383716984
3250	1986496601	3218124494
3750	953529003	1544716985
4250	502653144	814298093
4750	331688224.2	537334923
Sum	3.60663E+11	6.04274E+11
Available	6.666E+11	5.85E+11

Table D.1: Fuel use Hydro and Bio-LNG

D.5. VOT

In the latest results, the VOT value increases relative to the starting position. Whereby the sensitivity of the model can be controlled for this variable.

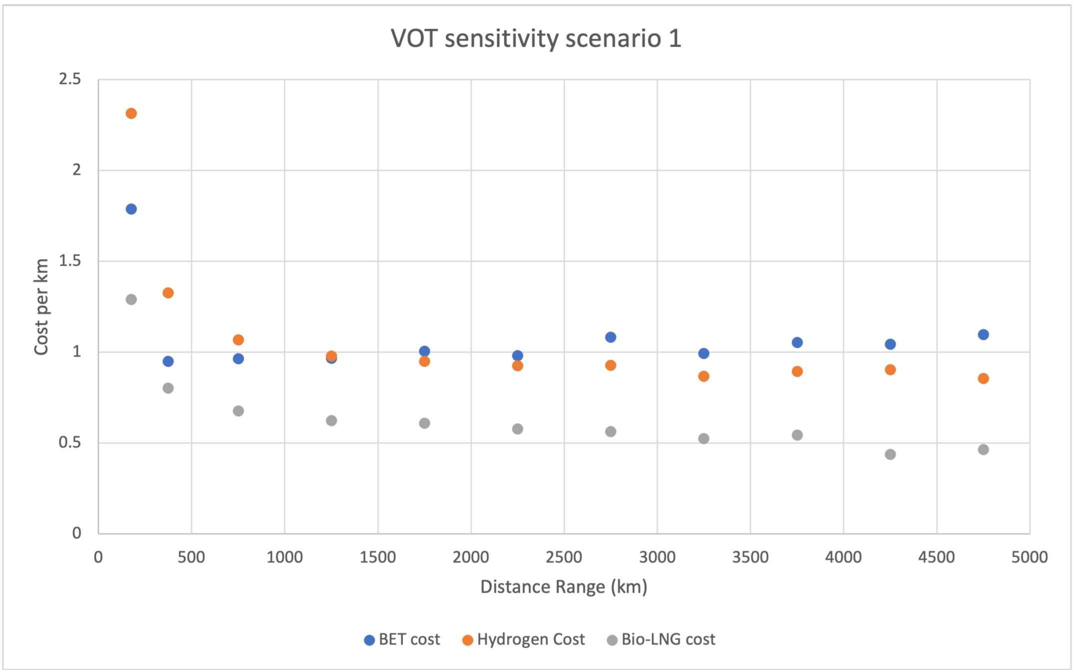

Figure D.16: Increase of VOT scenario 1

For both scenarios, it remains true that the initially cheapest alternative is still the cheapest in future scenarios, that is, for scenario 1 Bio-LNG and for scenario 7 BETs. However, in scenario 1, over long distances, it is more advantageous to drive with hydrogen when comparing hydrogen and BETS. This has changed compared to earlier experiments. In case of an increased VOT it is advantageous to use BETs over hydrogen only on short distances. The system is, therefore, in the current state, relatively sensitive to changes in the VOT. Therefore, products with a short shelf life may be less suitable to be transported by BETs. However, with the expected technological developments, the system is relatively insensitive to changes in the VOT.

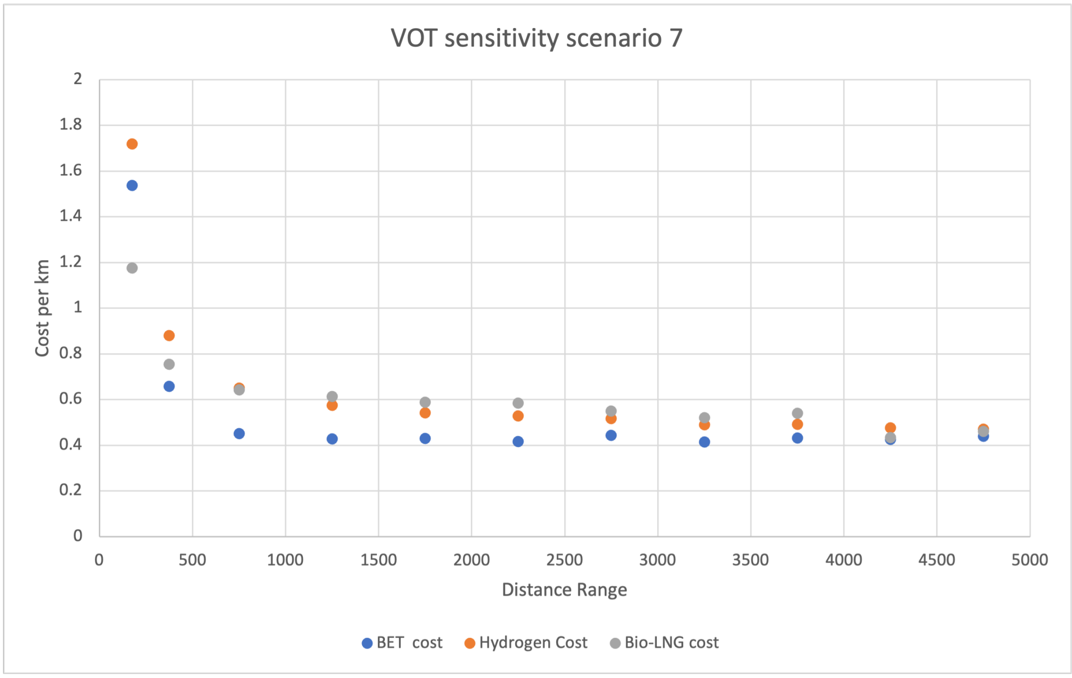

Figure D.17: Increase of VOT scenario 7