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Stochastic Network Design Modelling for Decarbonization of the Norwegian Freight Transportation System

Master's thesis in Industrial Economics and Technology Management
Supervisor: Steffen J. Bakker
Co-supervisor: Ruben van Beesten
June 2022

Master's thesis

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Preface

This thesis is the concluding part of our Master of Science degree in Economics and Technology Management at The Norwegian University of Science and Technology (NTNU). The degree specialization is in Managerial Economics and Operations Research. This master's thesis was written during the spring semester of 2022 as a continuation of the work presented in our specialization project (TIØ4500) written in the fall semester of 2021.

We would like to thank our supervisors Steffen J. Bakker and Ruben van Beesten for genuine enthusiasm about our work and valuable feedback and guidance throughout the semester. We would also like to thank Asgeir Tomasgard for the inspiration for this thesis. We are also very grateful to The Institute of Transport Economics (TØI) and PhD Candidate Jonas Martin for providing us with valuable data input and responding to all of our inquiries.

Ingvild Synnøve Brynildsen, Anette Sandvig and Marit Siqveland

Trondheim, 11th of June 2022

Abstract

In this thesis we present the problem of modelling decarbonization of the Norwegian freight transportation system over time. The problem entails assigning the flow of goods between Norwegian counties and international zones to modes and fuels. This is done in a way that ensures a solution with minimal system costs that complies with the emissions constraints the Norwegian government has committed to through the Paris Agreement. Decarbonization is achieved through increased usage of sustainable fuels, which are constrained in terms of their technical maturity, scalability, needed infrastructure and how quickly they can be phased into the existing fleet of vehicles. Investments in infrastructure allow for a greater usage of certain modes and fuels.

The problem is modelled as a stochastic strategic multi-modal freight transportation network design model, with added elements from energy system modelling such as explicit emission constrains and maturity limits on new technologies. The maturity limits are uncertain and are thus modelled in a stochastic manner, which allows the model to take this uncertainty into account when making the first-stage decisions. Including emission constraints and the possibility of using multiple mode-fuel combinations has not yet been done in freight transport modelling to the best of our knowledge. Freight transport models with stochastic fuel maturities are also not found in the available literature.

We test our model formulation on a case study where all demand for freight transport in Norway is included, both domestic transport and all international transport to and from the country. Realistic data for demand, costs, capacities and emission factors were gathered from multiple sources and systematized for our case study. Our results show that a complete decarbonization of the Norwegian transportation system by 2050 is near impossible to achieve. This is mainly due to the maturity of new sustainable duels being too low to cover all demand. Our results indicate that sea is the preferred mode of transportation, both internationally and domestically, and that ammonia is the most cost-effective new fuel for sea transport. We also observe that considerable investments in rail infrastructure are made in the stochastic model, though not in a deterministic version of the model. This suggests that the stochastic approach captures elements of the problem that the deterministic model fails to do, and that rail investments ensures added flexibility no matter the realization of fuel maturities.

Sammendrag

I denne masteroppgaven presenterer vi en model for dekarbonisering av det norske godstransportnettverket over tid. Problemet innebærer å allokere flyt av varer mellom norske fylker og utenlandske soner til ulike transportformer og drivstoff. Dette er gjort på en måte som garanterer en løsning som etterkommer utslippsreduksjonskravene som den norske regjeringen har forpliktet seg til gjennom Parisavtalen. Dekarbonisering oppnås gjennom innfasing av nye, bærekraftige drivstoff, som er begrenset med tanke på teknisk modenhet, skalerbarhet, nødvendig infrastruktur og mulig innfasingsrate inn i den eksisterende flåten. Investeringer i infrastruktur muliggjør en økning i bruken av visse transportformer og drivstoff.

Problemet er modellert som en stokastisk og strategisk nettverksdesignmodell for godstransport med flere transportformer. Modellen innehar elementer fra modellering av energisystemer, slik som eksplisitte utslippsrestriksjoner og begrensninger relatert til hvor modne nye drivstoffteknologier er. Modenhetsnivået for ulike drivstoff er ukjent og derfor modellert på en stokastisk måte slik at modellen tar hensyn denne usikkerheten når her-og-nå beslutningene skal tas. Så vidt vi vet, er det å inkludere utslippsrestriksjoner, samt muligheten for å benytte flere kombinasjoner av transportformer og drivstoff, noe som ikke er blitt gjort før innen transportmodellering. Transportmodeller med stokastiske modenhetsnivåer for ulike drivstoff er heller ikke funnet i den tilgjengelige litteraturen.

Vi tester modellformuleringen vår på en casestudie som inkluderer all etterspørsel av godstransport i Norge, både innenlands og internasjonal transport til og fra landet. Realistiske data for etterspørsel, kostnader, kapasiteter og utslippsfaktorer er samlet inn fra flere kilder og systematisert for casestudiet. Resultatene våre viser at en total dekarboniserting av det norske transportsystemet innen 2050 er nærmest umulig å oppnå. Dette skyldes i hovedsak at nye, bærekraftige drivstoff ikke blir modne nok til å møte all etterspørsel. Resultanene våre peker på sjøtransport som den mest ideelle transportformen, både for innenriks og internasjonal transport, og på ammoniakk som den mest kostnadseffektive av de miljøvennlige drivstoffene innen sjøtransport. Vi observerer at store investeringer i jernbaneinfrastruktur gjennomføres i den stokastiske modellen, men ikke i den deterministiske versjonen av modellen. Dette tyder på at den stokastiske modellen fanger opp elementer ved problemet som det deterministiske modellen ikke gjør, og at jernbaneinvesteringer gir en mer fleksibel løsning, uavhengig av realiseringen av de usikre modenhetsnivåene.

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Abbreviations

General Terms

GHG	Greenhouse gas
TØI	The Norwegian Institute of Transport Economics
NGM	The Norwegian National Freight Transport Model, developed by TØI
NETS	Non emission trading system
ETS	Emission trading system
MNOK	Million Norwegian kroner
BNOK	Billion Norwegian kroner

Fuel Technologies

BEV	Battery electric vehicle
FAME	Fatty acid methyl ester
HVO	Hydrotreated vegetable oil
LBG	Liquefied biogas
CBG	Compressed biogas
HFO	Heavy fuel oil
MGO	Marine gas oil
LNG	Liquefied natural gas
CL	Contact line

Stochastic Modelling Terms

SP	Stochastic program
SMIP	Stochastic mixed integer program
PH(A)	Progressive hedging (algorithm)
EF(S)	Extensive form (of the scenario formulation)

Chapter 1

Introduction

Transportation of goods is a central part of a country's economy. In 2019, over 332 million tonnes of goods were transported domestically in Norway, and an additional 97 million tonnes were exported and imported [Jørgensen & Solvoll, 2021]. The demand for transport is only expected to grow in the future as a result of population growth and increasing economic activity. As of today, the majority of domestic freight transport is performed by trucks, and forecasts show that a large portion of future growth is expected to happen on roads [Jørgensen & Solvoll, 2021]. This poses a great challenge as road traffic is a large source of CO_2 emissions.

In 2015 Norway signed the Paris Agreement, committing to reduce greenhouse gas (GHG) emissions and striving to achieve a goal of no more than a 1.5 degree global temperature increase. Specifically, Norway has committed to reducing GHG emissions by 50-55 % of 2005 emission levels by 2030 and be climate neutral by 2050. As emissions from the transportation sector constitute a considerable share of Norwegian GHG emissions, a transition from fossil to renewable fuel sources is necessary to achieve the recommended climate goals. Other suggested measures to reduce emissions from transportation includes transferring freight transport from road to sea and rail, and increasing transport efficiency [Samferdselsdepartementet, 2021a].

The purpose of this thesis is to gain insight into possible future developments in usage of new fuel technologies and infrastructure investments. This is done through modelling of the Norwegian freight transportation system over time while taking into account the emission restrictions posed by the Paris Agreement. Such a model would be useful for the Norwegian government when constructing policies to ensure a cost-effective decarbonization of Norwegian freight transport. The model is multi-period to allow for possible changes in infrastructure over time. This multi-period perspective also allows for new mode and fuel combinations to mature, and for a direct modelling of the Paris Agreement emissions restrictions. Though the current model in use in Norway, the National Freight Transport Model (NGM), has been used for similar types of analyses, it is not multi-period and does not incorporate new sustainable fuel technologies.

Our modelling approach is based on strategic transportation network design modelling as described by Crainic [2003]. We base our model on a strategic planning level from the perspective of a government policy maker, but we also include elements of tactical transport modelling. The model is stochastic where the future availability of new sustainable fuel technologies is uncertain. In addition, we draw inspiration from the field of energy system modelling (Rosenberg et al. [2020]) where emissions, infrastructure investments and technology development are considered more directly than in transport modelling.

Our main contribution to the transport modelling literature is a model that directly applies the emission restrictions from the Paris Agreement over multiple time periods. The model is also stochastic and considers possible future maturity development of new fuel technologies, which puts a limit on the usage of these fuels. Additionally, investments in infrastructure, such as terminals, railway lines and charging and filling infrastructure are included. These elements are found in energy system modelling, but have not previously been applied to transport modelling. We have also collected and structured large amounts of data related to costs for various combinations of fuels and vehicles, transfers and carbon price. The various fuels and vehicles also have associated emission factors, which have been gathered from multiple data sources. Additionally, we have collected data related to the capacity of current infrastructure for rail and sea transport in Norway, as well as the cost and resulting capacity expansion of different types of investments in infrastructure for rail, sea and charging and filling for new fuels on road. Lastly, we have constructed maturity levels for all fuels based on possible future developments as depicted by multiple reports.

We begin this thesis with an introduction to the Norwegian freight transportation system in Chapter 2 and fuel technologies in Chapter 3. Then we provide an overview of the field of transport modelling and other related literature in Chapter 4. Chapter 5 outlines the main methods we use in our work. In Chapter 6 we present a detailed description of the national freight transportation problem. The mathematical model developed to solve this problem is provided in Chapter 7 along with a discussion of our modelling choices. In Chapter 8 we define the scope of our case study and outline the data we use and their sources. In Chapter 9 we present and discuss our results. Finally, in Chapter 10, we provide some concluding remarks and discuss some areas of further work.

Chapter 2

Freight Transport in Norway

This chapter presents essential elements of the Norwegian transportation network. This includes which modes and vehicles are used, the current transportation infrastructure, the magnitude of today's GHG emissions from the transport sector and which emission reduction measures are in use.

2.1 Transportation Modes

The Norwegian transportation system is made up of several different modes of transportation. A transport mode is a group of vehicles operating on the same infrastructure [Jørgensen & Solvoll, 2021]. By vehicles we mean all machines used to transport goods, such as different kinds of trucks, ships and locomotives. Examples of modes are road, sea, rail and air. Many transportation systems, such as the Norwegian freight transport system, are multi-modal, meaning they support the use of several modes [Bektas & Crainic, 2007]. This term is closely linked to intermodal transportation, which refers to transportation from origin to destination using a sequence of at least two transportation modes. This integration of multiple transportation modes creates a more efficient transportation system [Bektas & Crainic, 2007].

The Norwegian domestic freight transport is dominated by road and sea transport, while sea dominates export and import. The distribution between transport modes is provided in Table 2.1. Transport by air is of a negligible size, and is therefore excluded from further discussion. We distinguish between the amount of transported goods and transport performance. The first term is measured in tonnes and indicates how many tonnes are transported with the different modes, here shown as a percentage of total transported amount. Transport performance is measured in tonne kilometres (tkm), which favours transport modes that transport large amounts of goods long distances, such as sea transport.

Table 2.1: Share of Norwegian domestic and international freight transport by mode. From Statistisk sentralbyrå [2020b] and Statistisk sentralbyrå [2022].

	Road	**Sea**	**Rail**	**Air**
Domestic (tonnes)	76.8 %	19.6 %	3.7 %	0.00 %
Domestic (tkm)	52.5 %	41.8 %	5.7 %	0.03 %
International (tonnes)	7.7 %	90.7 %	1.5 %	0.13 %

As seen by Table 2.1, transport by road is the most used mode of domestic freight transport in Norway. Truck transport is especially common for shorter distances, such as local deliveries and transportation to and from construction sites. Reasons for this include the flexibility of truck transport which allows for door-to-door delivery and makes it independent of strict schedules [Jørgensen & Solvoll, 2021]. An extensive road network also makes it possible to use trucks nearly everywhere. A disadvantage of truck transport is that each truck carries a relatively small amounts of goods. In long-distance transport this will lead to higher emissions per tonne kilometre than other modes of transportation [Jørgensen & Solvoll, 2021]. In this thesis we only consider long-distance transport between cities. Hence, we do not discuss short distance road transport.

Freight transport by sea is also very important, both for domestic and international transport, and is characterized by large amounts of goods transported long distances [Jørgensen & Solvoll, 2021]. This gives both low emissions and low costs per tonne transported by sea. A typical Norwegian cargo ship can carry the same freight as 400 trucks [Oslo Havn, 2018]. The disadvantage of sea transport is the long transportation time and having to load and unload the goods onto the ships. In Norway, sea transport is mostly used for dry and wet bulk products, such as petroleum products [Regjeringen, 2019a].

Rail is responsible for a relatively small amount of the domestic Norwegian freight transport. Today, a large portion of the freight transport on rail consists of import of iron ore from Sweden and export of timber [Samferdselsdepartementet, 2021b]. Similarly to sea transport, rail transport can transport large amount of goods over long distances. An average Norwegian freight train can carry the same amount of goods as 20-25 trucks [Jørgensen & Solvoll, 2021]. Additionally, most trains in Norway run on electricity, making it an environmentally friendly mode of transportation. The major disadvantage of rail transport is the poorly developed Norwegian railway network, making rail only one part of a transport chain where trucks have to be used in both ends. The majority of the railway network is also single tracked and shared with passenger trains, which heavily restricts the number of freight trains on most lines [Jørgensen & Solvoll, 2021].

For Norwegian export and import, sea is the dominant transport mode. In 2021, around 90 % of all exported and imported goods in tonnes were transported by sea, as seen in Table 2.1. Norway mainly exports goods to Europe, with Sweden, Germany, The Netherlands and Great Britain being the biggest markets [Basso et al., 2021]. These are also the most important European origins of import along with Denmark [Statistisk sentralbyrå, 2019a]. Outside of Europe, China and the United States are the most important markets.

Norway has many oil and gas platforms on its continental shelf, from the Barents sea in the north, through the Norwegian sea and to the North sea in the south. Transport to and from platforms is done either by wet bulk ships or by pipe to one of the 8 onshore facilities, which are located along the west cost [Oljedirektoratet, 2022]. Some of the oil and gas transported through pipes are transported directly to our export markets in e.g.

Germany or Great Britain [Oljedirektoratet, 2021]. The transport done by pipes is not considered in this thesis as it does not have any emissions and does not occupy capacity on transport vehicles such as ships.

2.2 Product Groups and Vehicles

The types of goods being transported impacts which types of vehicles can be used. It is therefore common in transportation research to differentiate between different product groups. TØI uses 39 product groups in the Norwegian National Freight Transport Model (NGM) [Hovi, 2018]. These are divided into seven main groups, which are dry bulk, wet bulk, fish, general cargo, industrial goods, temperature-controlled goods and timber [Madslien et al., 2015]. The product groups have restrictions on which type of vehicle can transport them. For instance timber can only be transported with specific trucks, railway wagons or ships built for timber transportation. Also, several product groups, like fish and other foods, require vehicles with cooling systems for transportation. Appendix B presents an overview of which vehicles can transport which product groups.

In addition to which product groups they can carry, vehicles also differ in their size and capacity. A full overview of vehicle capacity is found in Appendix B. Trucks used for heavy and long-haul transport can weigh up to 50 tonnes in total for most trucks, though up to 60 tonnes in total for timber trucks some semi trucks [Statens vegvesen, 2022b]. This total weight includes both the cargo and the truck itself, and will normally result in a capacity of around 30 tonnes of goods [Barbøl, 2019]. While trucks do not vary greatly in size, ships can differ vastly. Ships can generally be divided into cargo ships, used to transport packaged goods in containers or on pallets, and bulk ships carrying large quantities of unpackaged goods in dry or wet form [Regjeringen, 2019a]. For cargo ships that operate in Norwegian waters, the average size is around 10 000 tonnes of goods, and the average bulk ships carry 57 500 tonnes. Oil tankers are the largest ship type, with the average size of 118 000 tonnes [Regjeringen, 2019a].

For trains, the capacity is determined by the length of the train, i.e. the number of wagons. Different wagons are used for different product groups. System trains carry wagons that are specialized for one type of transport, like iron ore and timber [Jernbanedirektoratet, 2021a]. These types of trains are normally used by a single customer i need of transporting large amount of goods. Another important type of trains is combi trains, which transport containerized goods like general cargo and temperature controlled goods like fish [Jernbanedirektoratet, 2021a]. While the type of locomotive used is not dependent on product type, it is dependent on weight, were longer and heavier trains need 6 axle locomotives instead of the standard 4 axle locomotive [Jernbanedirektoratet, 2019a].

2.3 Transfers

The transfer of goods between different modes in a transportation chain is an important element of most transportation systems. Transfers lead to intermodal transportation as multiple modes are used from origin to destination [Kenton, 2020]. Transfers occur in intermodal terminals, such as railway terminals or harbours. Here, goods may also be consolidated, meaning that goods from different shippers, possibly with different origins and destinations, are loaded onto the same vehicle, for efficient long distance transportation [Zhu et al., 2014]. An intermodal transport chain seeks to take advantage of the characteristics of different modes of transportation. Normally, road transport, which is flexible and efficient, will be used in the first leg from origin to a terminal, and in the last leg from a terminal to the final destination. This is often needed as the origin and destination often are not reachable by other modes of transportation. Sea or rail transport are preferred for the long leg of a transport chain, as they are cost effective modes with a low emission rate per tonne transported [Jørgensen & Solvoll, 2021]. Though most types of goods are possible to transfer between modes, goods transported in containers are especially suited for transfers. Though container can refer to any box that carries freight, standards for containers were established early on and the standard is today the Twenty-foot Equivalent Unit (TEU) [Bektas & Crainic, 2007]. This standardization makes transfer operations in terminals fast and simple. A transfer of non-containerized goods, or transfer of goods between a container and another receptacle, is less common as it is costly and time consuming to empty and fill the receptacles multiple times [Grønland, 2018].

2.4 Emissions

The transport sector, including both passenger and freight transport, is responsible for 32 % of total Norwegian GHG emissions [Miljødirektoratet, 2021] and well over half the emissions in Non Emission Trading System (NETS) sectors [Klima- og miljødepartementet, 2021b]. NETS sectors are sectors that are not included in the EU system for emission trading (ETS), and includes, among others, transport and agriculture. ETS is a strong instrument to reduce emissions in a cost effective manner, as the markets put a price on CO_2 and pushes this price upwards as the number of available carbon credits is decreased [European Commission, 2021]. Though transport is not included in ETS as of today (2022), this will change in the coming years. The EU has presented proposals of including sea shipping in the existing ETS gradually between 2023 and 2026 [DNV-GL, 2021], as well as establishing a separate emission trading system for road transport and construction [Øvrebø, 2021]. The goal is to accelerate the emission reductions, and supplement existing incentives.

The main incentive used to reduce emissions in the transport sector today is the CO_2 tax, referred to as carbon price, which affects all emissions from the transport sector [Samferdselsdepartementet, 2021a]. The Norwegian government is planning on increasing this price per tonne CO_2 emitted from 766 NOK/tonne in 2022 to about 2000 NOK/tonne in 2030 [Regjeringen, 2021]. Other emission reducing incentives used by the Norwegian government includes a biofuel mandate, requirements of using certain sustainable technologies, especially in public procurement, and economic incentives from Enova. Enova is a government owned company providing economic support for individuals and companies wanting to invest in climate-friendly technology [Samferdselsdepartementet, 2021a].

The Norwegian government has a goal of cutting emissions from the transport sector in half by 2030 compared to 2005 [Samferdselsdepartementet, 2021a]. According to statistics from Statistisk sentralbyrå [2019b] including both freight and passenger transport, road transport is responsible for over half of transport emissions as well as 17 % of total Norwegian emissions, making it the third largest source of GHG emissions after the petroleum and industry sectors. Sea transport is responsible for 19 % of transport emissions. Rail transport only makes up 0.3 % of total transport emissions as it is mostly electrified [Statistisk sentralbyrå, 2019b]. The share of total transportation emissions attributed to freight transportation is around 39 % [Ritchie, 2021]. As passenger transportation is easier to decarbonize, freight transportation will make up a larger portion of total transportation emissions in the future [Ritchie, 2021].

2.5 Modal Shift

Another way of reducing emissions is through modal shift. While a transfer is a change of mode within a transportation chain, a modal shift refers to a change in which mode is used altogether. Normally, a modal shift is presented as using sea or rail transport instead of road. The Norwegian government has a goal of shifting 30 % of all freight transport by road that is over 300 km to sea and rail by 2030 [Samferdselsdepartementet, 2021a]. This would reduce emissions, as sea and rail have lower average emissions per transported tonne. Other benefits include decrease in noise pollution, increased local air quality and safer roads [Samferdselsdepartementet, 2021a].

The potential of this measure depends on the competition between the different transport modes. Askildsen & Marskar [2015a] estimate this potential to be small, as the different transport modes are highly specialized and thus operate in almost separate markets. Thus only a small percentage of transported tonnes are deemed suitable for modal shift. However, when looking at the transport performance in tonne kilometres it becomes more significant as the distances are long. About 5-7 % of domestic transport performance can be transferred from road to sea or rail [Askildsen & Marskar, 2015a]. Though the potential for emission reductions through modal shift is relatively small, it might still have an impact on certain routes between the major cities and across international borders [Handberg et al., 2019]. As previously mentioned, consolidating Norwegian import in harbours in Europe and Asia could also be a measure to move transport away from roads.

While sea and rail are appropriate modes for long distance transportation, the last leg of the distance will often have to be carried out by a truck, since the harbour or railway terminal might not be the final destination. This last-mile transport is outside of the scope of our model as this is a form of short distance transport.

2.6 Capacities and Infrastructure Investments

In this subsection we discuss the capacity and possible investments in the existing infrastructure for rail and sea. There are few capacity limitations on freight transport by road. Though some areas experience congestion, this mainly leads to capacity restrictions on roads within cities and the main roads in and out of cities [Samferdselsdepartementet, 2021a]. This is assumed to not affect the capacity on freight transport between cities in a notable fashion and will therefore not be further discussed.

2.6.1 Rail

Freight transport by rail is restricted both by the capacity on the railway lines, as well as the capacity at terminals. Access to the rail tracks is the biggest challenge as only a certain number of trains can use the tracks per hour. A single tracked rail has a capacity of 2-7 trains per hour in total for both directions, while for a double railed track this is increased to a capacity of 20-24 trains/hour [Jernbaneverket, 2012]. Since only 7 % of the Norwegian railway network is double tracked, and passenger trains are prioritized over freight trains, this poses a strong constraint on freight traffic on rail [Jernbanedirektoratet et al., 2020].

In addition to building double tracks, there are several other ways of increasing capacity on railway lines. One option is to increase the length of the trains from a typical 350-450 meter up to 650-750 meters. This will increase the amount of goods transported without needing additional trains. The downside is that this will often require longer crossing tracks and locomotives with higher pulling power [Jernbanedirektoratet, 2019a]. Longer trains could also be challenging at terminals where the tracks are 300-450 meters long Here, trains have to be split when loading and unloading. Building more crossing tracks will also increase the capacity, as the they allow for more trains to operate on a single tracked line [Jernbaneverket, 2012]. The adoption of the new digital signalling system, ERTMS, will also lead to a higher capacity [Jernbanedirektoratet, 2019a].

The Norwegian railroad network only extends up to Bodø, with the notable exception of Ofotbanen which stretches from Narvik to the Swedish border where it connects to the Swedish railroad network [Jernbanedirektoratet, 2018]. The Norwegian network is shown in Figure 2.1. There has been much discussion about a possible extension of the railway from Bodø, through Narvik, and all the way up to Tromsø. The last report on this subject was delivered to the Ministry of Transport by the railway directorate in 2019 [Jernbanedirektoratet, 2021c]. The suggested line will include a main line from Fauske (Bodø) to Tromsø and a side line between Bjerkvik and Harstad. Despite positive effects like lower transport costs, fewer accidents and reduced emissions, the line is not considered to be profitable from a socio-economical perspective. Whether the line will be built or not is largely up for political debate.

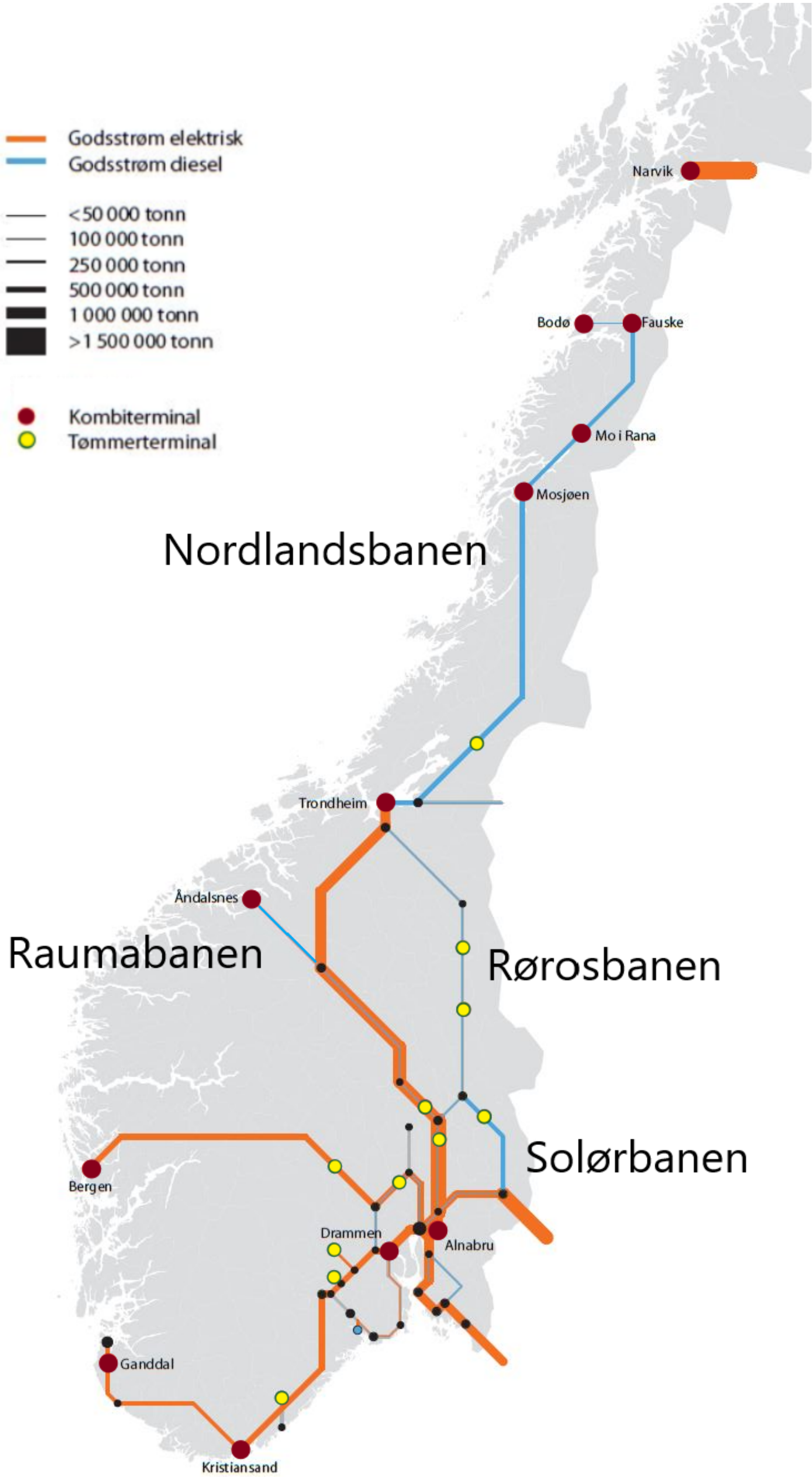


Figure 2.1: The current network of railway lines and terminals in Norway. Electrified lines are shown in orange and non-electrified lines are shown in blue. Combi terminals are shown in red and timber terminals in yellow. Figure adapted from Jernbaneverket [2016].

In addition to capacity increasing investments on the rail network, it is also possible to invest in electrifying the rail network to reduce emissions. About 35 % of the current network is non-electrified, with the longest non-electric line being Nordlandsbanen between Trondheim and Bodø. The other non-electrified lines are Rørosbanen from Hamar to Støren, Solørbanen which connectes Rørosbanen and Kongsvingerbanen and Raumabanen which connects Åndalsnes to Dovrebanen. These lines are shown in Figure 2.1. Meråkerbanen and Trønderbanen from Trondheim to the Swedish border is currenly being electrified and is expected to be finished in 2024 [Bane Nor, 2021a]. All of these lines operate freight trains, with Nordlandsbanen being especially important as 80 % of freight transport between Trondheim and Bodø is transported by rail [Jernbanedirektoratet, 2021b]. These lines are today only operated by diesel trains and hybrid trains using diesel. As an alternative to full electrification of these, partial electrification could achieve an emission free railway line with far less costs [Svingheim, 2019]. This solution requires trains with batteries that are charged by contact lines on sections of the line. Thus it is not necessary to build infrastructure for contact lines on the entire line.

Freight transport on rail is not only restricted by the railway line infrastructure, but also the capacity at the terminals. There are 12 combi terminals in Norway, as seen in Figure 2.1. These handle several types of goods such as dry bulk, wet bulk, containers and general cargo [Askildsen & Marskar, 2015b]. Alnabru terminal in Oslo is by far the largest and most important railway terminal in Norway. The terminal has for a long time operated close to maximum capacity, and plans to expand capacity gradually up to a double capacity by 2060 have been made [Jernbanedirektoratet, 2019d]. Other terminals, such as Bergen, Drammen and Narvik, are also noted to be close to their maximum capacity and are in need for capacity increasing investments [Jernbanedirektoratet, 2019a]. There is also a need for smaller investments in most terminals to allow for longer trains of up to 750 meters to be serviced without having to be split [Jernbanedirektoratet, 2019a]. Other capacity increasing investments in terminals includes switching to bigger and more efficient cranes and increasing the number and length of tracks [Jernbanedirektoratet, 2019d].

In addition to the combi terminals, there are several smaller terminals for timber. Most of these are located in Innlandet, Viken and Vestfold og Telemark, where the majority of trees in Norway are felled [Askildsen & Marskar, 2015b]. A large portion of timber is exported to Sweden and some timber terminals near the border reached their maximum capacity [Jernbanedirektoratet, 2019a]. An increase in capacity and upgrade of old terminals is neccesary. New timber terminals in Kongsvinger, Hauerseter and in Telemark are in the planning phase [Jernbanedirektoratet, 2019a].

2.6.2 Sea

Freight transport on sea does not require much infrastructure. Even though ships follow specific fairways, these do not restrict the capacity of sea transport in any way as the Norwegian fairway network is very extensive [Jørgensen & Solvoll, 2021]. The main restriction for sea transport is the available capacity in harbours. While the capacity in most Norwegian harbours is good [Samferdselsdepartementet, 2021a], further increase in traffic to accommodate government goals of moving freight transport from road to sea could mean that increasing capacity at some harbours will be necessary. Oslo harbour is one harbour that is nearing its maximum capacity [Oslo Havn, 2018].

There are over 3 000 harbours and docks all along the Norwegian coast [Kystverket, n.d.]. This geographically spread network helps to make sea transport available to a majority of Norwegian cities and all counties except Innlandet. 32 harbours are referred to as main harbours (stamnetthavn), of which seven used to be referred to as designated harbours (utpekt havn), though this system is being discontinued. The total 32 harbours are shown in Figure 2.2.

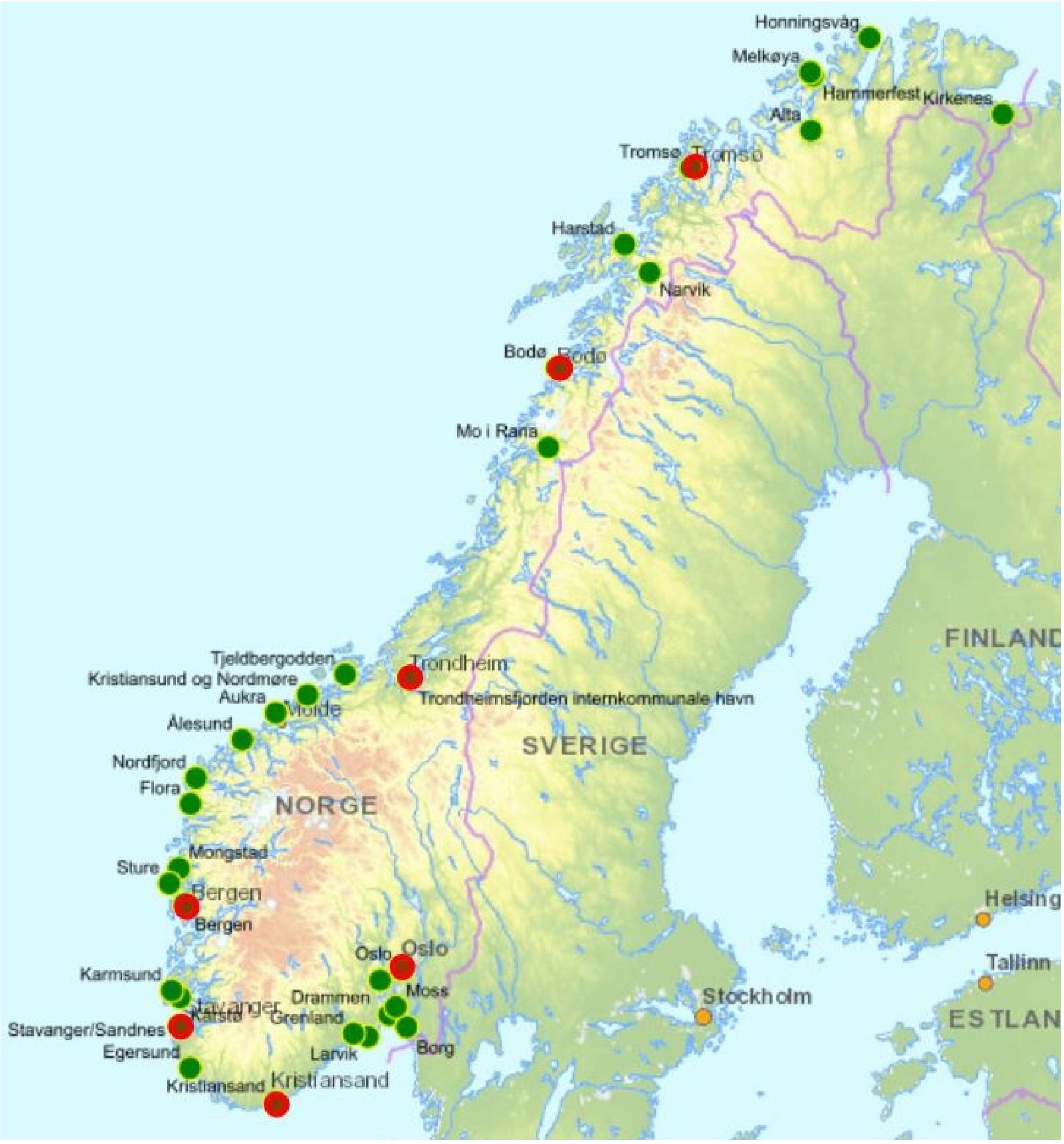


Figure 2.2: The network of main harbours in Norway. Formerly denoted designated harbours are shown in red, while the remaining main harbours are shown in green. From Kystverket [n.d.].

Chapter 3

Sustainable Fuel Technologies

The term sustainable fuels can mean different thing depending on the context. Here, we use the term to refer to fuels based on electricity, hydrogen and biofuels. Electricity, hydrogen and ammonia have no GHG emissions during propulsion, i.e. they have zero tank-to-wheel emissions [Hass et al., 2014]. They can also have zero emissions in production, depending on the production method, which would make them zero emission fuels in a well-to-wheel perspective as well. Biofuels have GHG emissions during propulsion that are similar to fossil fuels, but they are considered climate neutral due to the fact that CO_2 is absorbed from the atmosphere when the plants grow. Because plants naturally regrow, biofuels are also considered renewable. The total well-to-wheel emissions are dependent on production method, but advanced biofuels have much lower well-to-wheel emissions than conventional fossil fuels [European Environment Agency, 2012]. In this thesis, we take a well-to-wheel perspective and assume that electricity, hydrogen and ammonia have zero emissions and that biofuels have significantly lower emissions than conventional fossil fuels. Other sustainability aspects that will be discussed are land use in relation to the production of biofuels, and energy production and energy efficiency in relation to hydrogen and ammonia.

In the following sections we will discuss several factors related to the maturity of fuel technologies such as technical maturity, the rate at which vehicles are replaced in the fleet, the scalability of the technology's energy source and the available charging and filling infrastructure.

3.1 Technology Maturity

We define a fuel technology's maturity to be how much demand a mode and fuel combination can cover in a time period. The maturity of a fuel technology is dependent on the technical development. There are a multitude of frameworks used to evaluate the maturity of technologies. One of them is the Technology Readiness Levels (TRL) scale which is employed by Enova, a Norwegian government owned company providing economic support for individuals and companies wanting to invest in climate-friendly technology [Enova, n.d.]. The TRL scale rates technologies from 1 to 9, where TRL 1 to 4 refers the early development from the observation of basic principles to validation of the technology in a lab environment. The next levels, TRL 5 through 7, refers to the demonstration and prototyping phases, while the technology is fully developed and ready for market introduction in level TRL 8. The last level, TRL 9, includes the entire development after being introduced into the market [Enova, n.d.]. Hence, the framework does not consider different levels of commercial maturity, making it only suitable to consider the technical maturity of a technology. In relation to sustainable fuel technologies, we will discuss elements such as where on the TRL scale a technology currently sits, when it is likely to be available on the market, how the fuel is produced and its suitability for the Norwegian market.

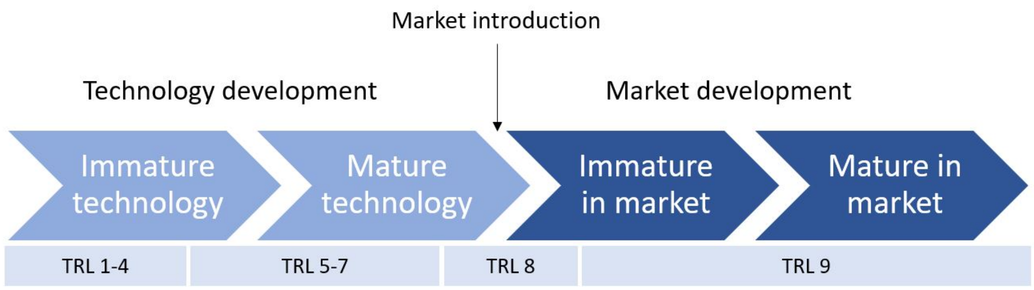


Figure 3.1: An overview of the Technology Readiness Level scale. Based on Enova [n.d.].

As the TRL scale emphasises, technical maturity is different from commercial maturity, and the former is a prerequisite to the latter. Though the usage of a technology is dependent on the technical maturity of the technology, other factors also hugely impacts the prevalence. One factor is the cost of new fuels in comparison to existing ones. The cost of a fuel is related to the fuel's technical maturity and availability, and the cost of buying new vehicles or adapting existing ones to make them compatible with new fuels. These costs can be affected by economic incentives from the government, such as support schemes and carbon price.

3.2 The Current Norwegian Fleet of Vehicles

The rate at which new technologies are phased into the fleet of vehicles depends on the length of the vehicles service life. New vehicles are purchased to replace the old ones, thus a shorter vehicle life span enables a faster phasing in of sustainable vehicles. Trucks have a relatively short typical life span at about 7-8 years [Barth et al., 2015], while ships lasts much longer with an average life span of 25-30 years [Norges Rederiforbund, 2015]. Trains are also long-lived, with many reaching over 30 years before they are replaced [Norske tog, 2020].

Today the Norwegian fleet of trucks consists of diesel trucks, with only a handful of non-diesel trucks in commercial use [Fridstrøm & Østli, 2021]. The replacement rate puts a limit on how fast new fuels can be adopted and scaled up. Thema Consulting Group [2022] estimates that it will take a minimum of 10-12 years before the current fleet is completely replaced. As the share of new trucks being non-fossil trucks is still very low, it might prove difficult to eliminate fossil trucks completely by 2050. This is also shown in Fridstrøm & Østli [2021], where the BIG model for fleet development forecasting is applied to different scenarios. These forecasts suggest that the percentage of trucks utilizing sustainable fuels in 2050 will be about 19 % if the current trend continues and about 74 % with additional political measures. The exchange rate can be increased through replacing trucks before they are 8 years, though this might not lead to any reduction in GHG emissions overall due to the higher consumption of trucks.

Data from Kystverket shows that in 2017, almost 7000 ships sailed in Norwegian waters. Of these, around 1000 ships are a part of the Norwegian domestic fleet Regjeringen [2019a]. Only a small percentage of the fleet is operated with zero or low emission technologies, with only 49 LNG ships and 16 ships with batteries in use in 2017 [Regjeringen, 2019a]. Most of these ships were ferries and offshore ships, though there are some freight ships that use LNG. This shows that the majority of Norwegian freight ships today use fossil based fuels. The domestic shipping is dominated by marine gas oil (MGO) and some use of liquified natural gas (LNG), while the international shipping also uses heavy fuel oil (HFO) [DNV-GL, 2014]. Due to the long life-expectancy of ships, it will take many years to replace the fleet entirely. Rebuilding existing ships could be a way to accelerate the transition into sustainable technology [DNV, 2022]. The road to a zero emission shipping sector might still be long, as the UN International Maritime Organization approved a goal of reducing emissions from international shipping by 50% by 2050 compared to 2008. The vision is to completely decarbonize shipping by the end of the century [Regjeringen, 2019a].

Though the majority of Norwegian trains are electric and 85% of freight on rail is transported with electric locomotives, there is still a considerable number of diesel operated trains in Norway. About 50 diesel operated locomotives are in use for freight traffic today [Svingheim, 2021b]. The majority of these are from the 90s, such as the Di 8 and CD 66 locomotives, and are thus nearing the end of their life expectancy [Hansen, 2013]. Replacing all diesel locomotives with electric locomotives is not possible yet, as there are still several railway lines that are not electrified. A solution could be to utilize hybrid locomotives that can run on both diesel and electric contact line. Such locomotives were recently purchased and put into operation in Norway by Green Cargo, who plan on eventually operating these trains on all their routes [Svingheim, 2021b]. Thus, conventional diesel trains could be phased out in a short amount of time.

3.3 Battery Electricity

Electricity is a zero-emission propulsion technology, meaning it produces no tail-pipe emissions from the system that provides the propulsion [Jordbakke et al., 2018]. In order for the technology to have zero well-to-wheel emissions, the production of the electricity need to be zero-emission. In Norway, nearly all energy that is produced is hydropower and wind power, which are renewable and emission free energy sources [NVE, 2019]. The electricity we actually consume may still come from fossil sources such as coal or gas, as Norway is connected to the European power supply system and thus imports electricity from other countries [NVE, 2019]. The environmental impact of battery production for battery electric vehicles (BEVs) is more controversial. The production process is very energy-intensive, leading to some BEVs having a higher production emissions than internal combustion engine vehicles [Ellingsen et al., 2016]. Battery technology for BEVs is still a young technology, and significant improvements in production methods and performance is to be expected. In Norway, several battery factories are in planning, and a research program with actors such as SINTEF and several industry partners are working on making the battery production more sustainable [SINTEF, 2022].

Electricity is a very scalable energy source. In a typical year, Norway produces about 10 TWh more electricity than what is consumed [Endresen Haukeli et al., 2020]. This makes electrification of the transport sector possible without having to import power in a typical year. As Norway is dependent on hydropower in particular, as well as wind power, the production will vary from year to year [Endresen Haukeli et al., 2020]. With a high degree of electification, we may need to import electricity in years with unfavourable weather conditions. A higher production of sustainable electricity in Norway may also be necessary to meet increased demand.

3.3.1 Road

The usage of BEVs as passenger cars is common. A majority of passenger cars sold in Norway in 2020 were BEVs (53%), and an additional 20% were hybrid electric [Pinchasik et al., 2021]. However, due to their limited driving range, higher price and smaller load capacity, long distance battery electric trucks are still few in numbers, with only 14 new trucks registered i Norway in 2020 [Pinchasik et al., 2021]. Several truck manufacturers, such as Volvo, Renault and Scania, have been working on developing long-range electric trucks for the European market for several years [Pinchasik et al., 2021]. Some have been introduced to the market already (by June 2022), while others will be introduced in next couple of years. These trucks typically have a driving range between 120 and 300 km, enabling regional and national freight transport when combined with a sufficient network of charging stations. Hence, electric trucks are fully technically mature today, though further improvements in battery technology can yield even better driving ranges and lower investment costs in the years ahead. This will be crucial if we are to reach the Norwegian government has set a goal of having 50% of all new trucks in 2030 be zero-emission trucks [Miljødirektoratet, 2020a].

3.3.2 Sea

While full battery solutions for ferries are in use, this is a lot more challenging for freight ships as the routes are longer and more unpredictable. The available battery technology also has too low energy density, meaning a very large and heavy battery is needed to provide necessary propulsion, though this would significantly reduce load capacity and profitability [Handberg et al., 2019]. A partial electrification of Norwegian ships is possible, and while this would lower fuel costs and emissions, it is not an environmentally sustainable alternative. Battery electric ships are not considered any further in this thesis.

3.3.3 Rail

Electric trains are an old technology and have been in use in Norway since the 1920s [Holøs et al., 2020]. Electric trains are powered through a contact line (CL) system, where a contact wire is suspended above the rails and provide electricity when in contact with the train's pantograph [Jernbanedirektoratet, 2019b]. There is no storage of energy in the train as the CL system continuously supplies the train with energy. For today's non-electrified lines there are several options for decarbonization through electricity. The first one is to upgrade the line with a CL-system, enabling standard electric trains to run on them. Though a tried and true technology, CL-systems has a very high investment cost meaning it would only be profitable to electrify highly trafficked railway lines [Jernbanedirektoratet, 2019b].

Another option for a electricity driven train is a battery train. Unlike the standard electric trains used with CL technology, battery trains have energy stored in a battery onboard the train [Jernbanedirektoratet, 2019b]. In a full battery concept, the train has enough energy stored onboard to drive to its destination without charging underway. Charging infrastructure will have to be build at the end points. This will, however, lead to very limited driving ranges, especially for freight trains. A battery train can also be combined with a partial electrification of the railway line. This concept involves utilizing a CL system on parts of the line for quick-charging of the train's battery while the train is moving [Jernbanedirektoratet, 2019b]. The charged battery will provide the train with enough energy until the next charging stretch of the line. Such a solution would be cheaper to invest in and maintain than a full electrification of a line [Svingheim, 2019]. The technology for implementing this concept is relatively mature, but the vehicle technology for freight locomotives may not be mature enough yet [Jernbanedirektoratet, 2019b].

3.4 Hydrogen and Ammonia

An alternative to storing energy in batteries, is utilizing hydrogen as an energy carrier. Hydrogen can be produced in a number of ways. The most common one is through turning natural gas into hydrogen gas (H_2) and CO_2 [Horne & Hole, 2019]. If the CO_2 from this process is not captured, the production will lead to large emissions. This is referred to as gray hydrogen [Horne & Hole, 2019]. Transformed natural gas combined with CO_2 capturing and storing is considered sustainable and denoted blue hydrogen. The other main way of producing hydrogen is through electrolysis. Here, water molecules are split into hydrogen and oxygen gas using electricity. This process is entirely emission free if the electricity used is from a renewable source, and is called green hydrogen [Horne & Hole, 2019]. A great challenge in hydrogen production is the energy loss. Hydrogen produced through electrolysis will carry 30-45 % less energy than the electricity put into the electrolysis. There is also an energy loss when converting hydrogen back to electricity in a fuel cell, meaning that using hydrogen is less energy efficient than using electricity directly [Olje- og energidepartementet & Klima- og miljødepartementet, 2020].

Hydrogen gas has a low volume power density, meaning large volumes are necessary when using it as an energy carrier [Horne & Hole, 2019]. To reduce the volume, hydrogen gas is often stored in compressed form in high-pressure tanks or in liquid form which requires cooling down to minus 253 degrees Celsius [Eriksen, 2021]. This makes storing hydrogen quite challenging. For storing large amounts of hydrogen for long distance transport, especially in shipping, hydrogen bound in ammonia (NH_3) might be a better option. Ammonia becomes liquid at only minus 33 degrees Celsius and has a high energy density [Eriksen, 2021]. This makes it much easier to handle and transport than pure hydrogen. The major drawback of ammonia as an energy carrier is the cost and energy loss of transforming hydrogen into ammonia [Aarnes et al., 2019]. Hydrogen can also be transformed into synthetic fuel (e-fuel), though a combination with $CO_2\dot{S}$ynthetic fuels will however not be considered in the rest of this as it is mainly considered for aviation and ammonia is considered a better alternative for maritime transport [Øystese, 2020].

Another challenge when using hydrogen and ammonia is safety. Hydrogen gas is very flammable, meaning that there is a high risk of explosions if the gas leaks. This happened at an hydrogen filling station in Sandvika outside of Oslo, which exploded in June 2019 [Ekroll, 2019]. This lead to a near full stop in sales of new hydrogen passenger cars in Norway. Ammonia, on the other hand, is not flammable but toxic and exposure to high concentrations can cause blindness, lung damage and death [Aarnes et al., 2019]. Strict safety measures is therefore necessary when handling both hydrogen and ammonia.

The scalability of hydrogen as a fuel in Norway depends on the volumes available. Norway produces about 225 000 tonnes hydrogen today, though nearly all of it is used as an input factor in industrial processes [Aarnes et al., 2019]. This tendency is clear in other countries, where only 4 % of globally produced hydrogen is sold openly at a market and nearly all is used in industry. Estimates from DNV GL shows an annual demand of about 56 000 tonnes hydrogen for the transport sector in 2030 [Aarnes et al., 2019]. Half of this will be used for heavy truck transport, 30% for sea transport, and the remainder for buses and hydrogen trains on Raumabanen and Rørosbanen. This would require much larger amounts of hydrogen to be sold on an open market.

Global ammonia production today sits at about 180 million tonnes. This is enough to replace 20-30 % of fossil fuels in the global shipping sector [Øystese, 2020]. Like hydrogen, the majority is used as input in industrial processes. 20 % of the world's production is transported on ships, meaning that there exists infrastructure and routines for handling ammonia along important shipping routes [Øystese, 2020]. In Norway, Yara have been producing ammonia for over 100 years to make fertilizers. Their production in 8.5 million tonnes ammonia annually [Hovland, 2021]. They have recently partnered with trading and transport company Trafigura, where the goal is for Yara to deliver ammonia for shipping and help develop infrastructure for ammonia. They are also planning on using green hydrogen instead of natural gas in the ammonia production in one of their factories, reducing emissions in their production significantly [Hovland, 2021]. Though large amounts of hydrogen and ammonia are produced today, the access to green or blue hydrogen and ammonia for the transport sector might be a limiting factor for the use of these energy carriers.

3.4.1 Road

Hydrogen vehicles are in use in some capacity in Norway. About 144 hydrogen passenger cars were registered as of 2018 [Regjeringen, 2019b]. For trucks, Scania had a collaborative project with wholesaler ASKO where they have rebuilt four diesel trucks into hydrogen fuel cell trucks in 2019. These were the first hydrogen trucks in use in Europe [Handberg et al., 2019]. Several truck manufacturers, such as Volvo and Mercedes are working on their first mass-produced hydrogen trucks, many of which are scheduled to be available on the market around 2030 [Pinchasik et al., 2021].

In addition to technical maturity, the price of hydrogen technology is a great barrier for utilizing it on a big scale. Hydrogen vehicles are more expensive than battery electric vehicles, and maintenance costs are high [Handberg et al., 2019]. On the other hand, the price for hydrogen at a filling station is roughly the same as the price for petrol when calculated per kilometre driven [Regjeringen, 2019b]. Technological development is needed in order to bring down vehicle costs.

3.4.2 Sea

Use of hydrogen as a fuel on ships is still in a development phase. Ferry company Norled launched their first hydrogen ferry in 2021, with the goal of utilizing hydrogen to cover 50 % of the ferry's energy needs in 2022. Other hydrogen ferries are also under planning [Statens vegvesen, 2022a]. Two hydrogen cargo ship in the short sea segment are also in planning in the Topeka project, where the goal is to sail a fixed route between Stavanger and Kristiansund by 2024. The ships are expected to be able to sail around 750 km totally emission-free [Ludt, 2020]. Long distance hydrogen ships are not expected to hit the market until 2030 [Myrset, 2020]. Hydrogen can be used in an internal combustion engine or a fuel cell, and can be stored as compressed gas or in liquid form. The price varies for these different options, but overall it is an expensive technology with high investment and operational costs [Handberg et al., 2019].

While hydrogen is only considered applicable to 20-50 % of the Norwegian fleet, ammonia could be used on the entire fleet [Handberg et al., 2019]. Other advantages of using ammonia over hydrogen, includes the existing infrastructure for shipping of ammonia [Handberg et al., 2019] and the higher energy density, requiring less storage space on board than hydrogen [Eide et al., 2019]. Still, both hydrogen and ammonia have a lower energy density than MGO, meaning that more of the ships weight and space must be used to carry fuel, or the ships must bunker a lot more frequently [Handberg et al., 2019]. Though not technically mature today, there are projects that are expected to produce engines capable of burning ammonia by around 2025 [Klima- og miljødepartementet, 2021a]. This makes it unlikely that widespread use of ammonia technology for ships will happen before 2030. Ammonia technology is also expensive, having a price level similar to hydrogen technology [Eide et al., 2019].

3.4.3 Rail

Hydrogen trains are possible to use on non-electrified railway lines, and they are based on much of the same fuel cell technology that other hydrogen vehicles are. The train would need to be constructed as a standard electric train with a battery to supply propulsion, but with additional equipment for storage of hydrogen and conversion of hydrogen into electricity. Thus, a hydrogen train is a battery train with a hydrogen-based battery charger on board [Jernbanedirektoratet, 2019b]. Though a cheaper solution than standard contact line due to much lower infrastructure investments, hydrogen trains are an expensive investment and fuel cost is much higher than both diesel and electricity. Hydrogen trains are also estimated to be significantly more expensive than diesel and biodiesel trains on Nordlandsbanen [Jernbanedirektoratet, 2019b]. There are no hydrogen locomotives for freight transport in Europe today, though two hydrogen passenger trains are in use in Germany [Jernbanedirektoratet, 2019c]. The technology is still in a prototype phase, and there is a lack of safety regulations and routines related to hydrogen handling in place. A significantly faster technological development is necessary in order to make hydrogen technology for heavy freight locomotives possible.

3.5 Biofuels

A biofuel is any fuel that is derived from biomass. In our context this refers to several types of liquid biofuel and biogases. The two main types of liquid biofuel are biodiesel and bioethanol [Handberg et al., 2019]. Since diesel is by far the most prevalent fuel in long distance road transport and biodiesel makes up 90 % of biofuels sold in Norway [Regjeringen, 2019b], we only consider biodiesel in this thesis. Biodiesel exists in different forms depending on how it is produced. FAME (fatty acid methyl ester) is the most common biodiesel in both Europe and Norway, with FAME based on rapeseed (RME) being the typical variant. Another type is HVO (hydrotreated vegetable oil), which is chemically very similar to fossil diesel. Because of this, HVO could potentially replace diesel partially or fully by mixing HVO with diesel or using 100 % HVO i diesel engines

[Handberg et al., 2019]. FAME could also be used this way, though with some more adjustments [Jernbanedirektoratet, 2019c].

Biodiesel can be produced either directly from crops which is denoted 1st generation biofuel, or from left-over or waste products such as frying oil or industrial food waste, which is called 2nd generation biodiesel or advanced biodiesel [SINTEF, 2016]. Non-advanced biodiesel is controversial because of its association to indirect land-use changes. Biofuels are often made from raw materials that can also be used as food, such as rapeseed, soy, corn, palm oil and wheat. This leads to agricultural land being used for production of biofuels rather than food [Regjeringen, 2019b]. Production of palm oil has also been linked to deforestation of rain forests [SINTEF, 2016]. Because of this, many have questioned whether biofuels in sum are good or bad for the environment. Mass production of non-advanced biodiesel is a mature technology, while advanced biodiesel is today limited to HVO-production from various waste oils [Jernbanedirektoratet, 2019c]. The limiting factor in the use of biodiesel is the amount of advanced biodiesel available. The production volume of biodiesel in Norway is very low, and nearly all biodiesel is imported [Jernbanedirektoratet, 2019c].

In Norway, biogas is mostly produced from sewage sludge and food waste [Biogass Oslofjord, 2021]. This means that biogas does not have the same issues as biodiesels when it comes to deforestation and indirect land-use changes. The raw biogas can be used directly for heat or electricity production, or it can be upgraded by removing CO_2 and other impurities such that only methane gas remains. This can be compressed and used as compressed biogas (CBG) or it can be liquefied through cooling and used as liquefied biogas (LBG) [Miljødirektoratet, 2020b].

In 2021, around 700 GWh of biogas was produced in Norway. Of this, almost 40 % was upgraded to CBG or LBG which can be used in transport [Biogass Oslofjord, 2021]. Estimates from Biogass Oslofjord [2021] shows a production of 1.5 TWh of biogas in 2035, though this could be increased through political measures. The access to biogas could be a barrier as the Norwegian government has a goal of having 10 % of all new trucks being biogas trucks by 2030, as well as extended use in sea transport [Miljødirektoratet, 2020a]. A total of 1.2 TWh per year of LBG is estimated for road and sea transport in 2030.

Both biodiesel and biogas are considered renewable fuels, as the energy is produced through photosynthesis as the plants grow [Hagman, 2019a]. While the plants grow, they also absorb CO_2 from the atmosphere, which is released again during combustion of the biofuel. Biofuels can therefore be considered climate neutral as they do not release more CO_2 than they capture, though the actual well-to-wheel emissions is dependent on the production method [Hagman, 2019a]. The tank-to-wheel emissions are similar to conventional fossil fuels [Hass et al., 2014]. The technical maturity of biofuels and its similarity to conventional diesel makes it an instrument to reduce GHG emissions quickly before transitioning into zero-emissions in the future.

3.5.1 Road

The most common way of utilizing biodiesel in Norway today is mixing it in with traditional fossil diesel. The Norwegian government requires a certain amount of biodiesel to be mixed in with all commercially sold diesel for road transport. This amount is 24.5 % as of 2022, with the additional requirement that 9 % of all biodiesel sold should be advanced biodiesel [Klima- og miljødepartementet, 2021a]. As advanced biodiesel is counted double, in reality the requirement for advanced biodiesel is 4.5 %. Biofuels are more expensive than fossil fuels, with advanced biofuel being the most expensive variant.

There are today several truck manufacturers offering trucks that can use 100 % biodiesel, including Scania and Mercedes-Benz who support 100 % biodiesel in their Euro V and VI engines [Jernbanedirektoratet, 2019c]. Biodiesel mixed with fossil diesel does not require any additional infrastructure, while for 100 % biodiesel, there are about 24 fuel stations offering this today [Regjeringen, 2019b]. Due to the high prevalence of biodiesel as a fuel for cars and trucks, we can consider this a highly mature technology.

The most important market for biogas is busses, but the market for biogas fueled long distance trucks is growing [Regjeringen, 2019b]. In 2018, about 300 biogas trucks were registered [Regjeringen, 2019b]. Infrastructure for biogas exists in Norway, but is not yet capable of servicing a large fleet of biofuel driven vehicles. There are 25 publicly available filling stations for CBG and 4 for LBG as of 2022 [Biogass Oslofjord, 2022]. The current network of biodiesel and biogas filling stations is shown in Figure 3.2.

3.5.2 Sea

Today, biodiesel is used by a couple of ferries in Norway. They utilize HVO, as this is very similar to fossil diesel and hence can be used in conventional marine diesel engines with small or no technical adaptation of the machinery [Handberg et al., 2019]. Using FAME as a biofuel for ships is considered technically challenging by Regjeringen [2019b]. Biodiesel is also a mature technology for freight ships, but this is not commonly used today.

The prevalence of HVO as a marine fuel in the future will be dependent on the emission reducing requirements in the industry. The Norwegian government is planning on making requirements on certain amounts of biofuels to be mixed in with marine fuels from 2022, similarly to the requirements of biofuels in fuels for trucks [Miljødirektoratet, 2020a]. 10 % of the required biofuels is estimated to be advanced HVO, and the rest LBG. The usage of HVO in the future is also dependent on whether the necessary volumes are available and the price of HVO compared to other fuels [Handberg et al., 2019]. Today, HVO is considerably more expensive than LNG and MGO [Eide et al., 2019].

Similarly to how HVO can be used in marine diesel engines, LBG can be used in engines designed for LNG. LBG can also be mixed into LNG for a gradual decarbonization alternative [Handberg et al., 2019]. Due to their similar properties, LBG can also use the same bunkering infrastructure as LNG. The use of LGB is mainly limited by price and available volumes compared to alternatives.

3.5.3 Rail

Biodiesel is not is use as a fuel on Norwegian trains today, but it could be a substitute to the fossil diesel used for non-electrified rail. A biodiesel based train is almost identical to a regular diesel train, making it an easy, cheap and fast way of transitioning from fossil fuels [Jernbanedirektoratet, 2019b]. There are some countries, such as the Netherlands and Sweden, that operate biodiesel trains that use HVO [Jernbanedirektoratet, 2019c].

Biogas is also not in use for trains, neither in Norway nor in Europe [Jernbanedirektoratet, 2019c]. There are also no plans of this, and it will therefore not be considered in this thesis.

3.6 Summary of Fuels

To summarize, battery electricity is suitable for short and medium distances on road now, but will most likely be applicable to longer distances in the near future. It is also suitable for rail, where partial electrification might be a cheaper alternative in the years to come. Hydrogen is best suited for heavy loads and long distances, such as for sea and rail transport, as well as the longest and heaviest of road transport. Current technological development suggests that hydrogen might be used on long distance road transport between 2030 and 2050, and that ammonia might become important in shipping. Hydrogen is not very likely to be used as a fuel for rail by 2050. Biodiesel are currently in use as a drop-in fuel for road, and there is a potential for 100 % biodiesel trucks. The biogas truck market is growing, as these trucks are suitable for long distances. The planned biofuel mandate for sea transport is likely to increase the usage of biofuels significantly, especially for LBG. Biodiesel may be used on rail, either as 100 % or as a drop-in fuel.

An overview of all considered fuels, both conventional and new, is shown in Table 3.1. Each fuel is presented with an associated TRL score, scalability level and an estimate for when the first vehicles utilizing the fuel will be available on the market. The TRL scores are based on Aarnes et al. [2019], The Sustainable Shipping Initiative [2021] and Plötz et al. [2018]. The scalability level is high if it is considered unproblematic to produce enough of the fuel to serve a large fleet of vehicles, and low is this is assumed to be difficult. The level is based on previous discussions. The estimates for when various fuels will be available on the market are based on Pinchasik et al. [2021], Myrset [2020], Klima- og miljødepartementet [2021a], Bane Nor [2021b] and Jernbanedirektoratet [2019c].

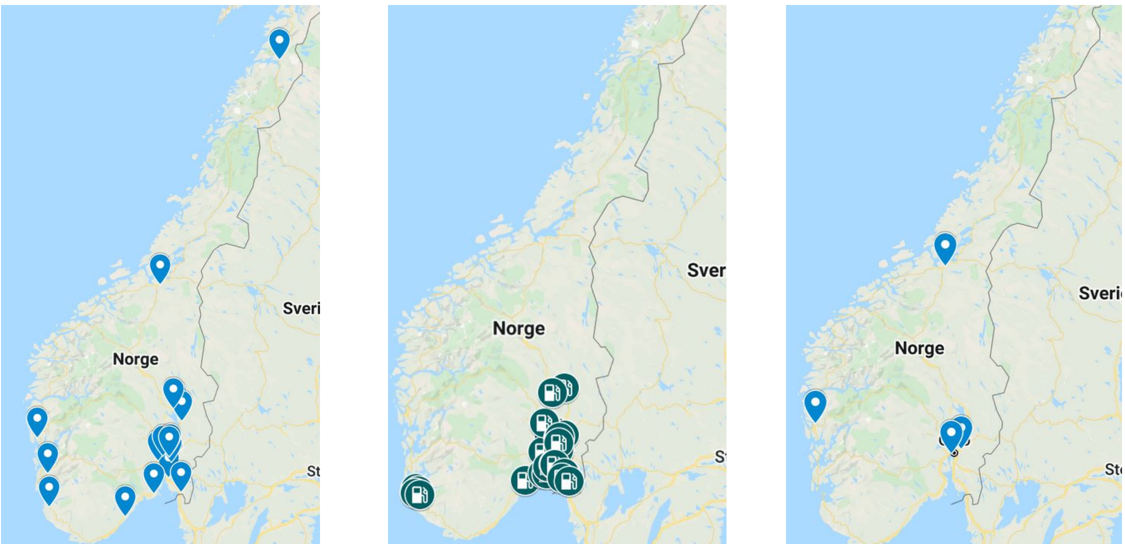
Table 3.1: An overview of the various fuel technologies for each mode with an associated TRL score, scalability level and estimated market introduction.

Mode	Fuel	TRL	Scalability	Available from
Road	Diesel	9	High	Today
	Battery electric	9	High	Today
	Hydrogen	6	High	2025-2030
	Biodiesel	9	Low	Today
	Biogas	9	Low	Today
Sea	Heavy fuel oil (HFO)	9	High	Today
	Marine gas oil (MGO)	9	High	Today
	Liquefied natural gas (LNG)	9	High	Today
	Hydrogen	6	High	2030
	Ammonia	6	High	2025-2030
	Biodiesel	9	Low	Today
	Biogas	9	Low	Today
Rail	Diesel	9	High	Today
	Electric train (CL)	9	High	Today
	Battery train (partial electrification)	7	High	2030-2035
	Hydrogen	6	High	2040-2050
	Biodiesel	9	Low	Today

3.7 Charging and Filling Infrastructure

The lack of an existing infrastructure for charging and filling stations, collectively referred to as energy stations, is one of the greatest barriers for utilizing sustainable fuels [Thema Consulting Group, 2022]. For short distance transport overnight charging at a depot might be sufficient, though in long-distance transport, a minimum number of energy stations will be required in order to make the distance travelable due to limited driving ranges. Hence, an energy station infrastructure is a prerequisite for the use of sustainable fuels in long-distance transport. This means that a the infrastructure needs to be built before the demand arises, which requires significant public investments [Thema Consulting Group, 2022]. It is also challenging as energy stations will need to be built before it is known exactly which technologies will be the most prevalent. The stations therefore need to be somewhat flexible, to allow for possible adaptations to other fuels in the future.

Due to the high prevalence of electric passenger cars in Norway, there already exists a large network of publicly available charging stations. However, an energy station network for trucks should be separate from the existing infrastructure for passenger cars. This is mainly for safety reasons, as passenger cars and people would be at risk of injuries when mixed with heavy trucks [Thema Consulting Group, 2022]. This leads to the question of where truck energy stations should be placed. Firstly, the stations need to be placed with a maximum distance between them to ensure that the vehicles have the necessary range to make it to their destination. This is estimated to be 100 km for battery electric vehicles, 150 km for compressed biogas and hydrogen, and 300 km for liquid biogas [Thema Consulting Group, 2022]. Using these estimates, we arrive at a minimum energy station network for Norway at an estimated cost of around 8 - 12.9 BNOK [Thema Consulting Group, 2022]. These costs do not include the costs of land, as this will vary greatly depending on the location. A collaborative effort with local municipalities is important to get access to land near large intersections, terminals or other transport hubs. There already exists some energy stations that offer biofuels and hydrogen. These are concentrated around the largest cities in Norway, especially around Oslo. This is seen in Figure 3.2.



(a) HVO stations. (b) Biogas stations. (c) Hydrogen stations.

Figure 3.2: Current filling station infrastructure as of 2022. The biogas map is from Biogass Oslofjord [2022].

For sea, little bunkering infrastructure exists for new sustainable fuels. Two hydrogen filling stations will be established in Stavanger and Ålesund as a part of the Topeka project [Ludt, 2020]. For biofuels, no additional infrastructure is required as biofuels can be mixed in with conventional fuels or utilize the same bunkering infrastructure as conventional fuels. As of 2018, ferries that utilized 100 % HVO bunkered directly from a tank truck, and no bunkering facilities report offering LBG [Regjeringen, 2019b]. For rail, no infrastucture exists today. It is assumed that if hydrogen becomes and option for rail transport, filling stations will be supplied by hydrogen providers at the current locations of diesel filling stations (E. Fure, personal communication, May 20, 2022).

Chapter 4

Literature Review

In this section we present an overview of the contemporary literature on freight transport planning models. This is largely based on the work done in our specialization project written as a part of the course TIØ4500. We give a general introduction to the field, before presenting some relevant tactical and strategic transport models. We then turn our focus to network design models and discuss several characteristic of this model type. Finally, we present an overview of the related literature and our contributions to freight transport modelling.

4.1 Literature Search Strategy

Our search strategy for relevant literature is based on conducted searches on Web of Science and Google Scholar with *freight transport network design modelling* as the main search words in combination with other related terms, such as *emission constraints*. A full overview of the related terms is given in Table 4.1, categorized under the problem characteristics of planning, sustainability and modelling. We have mainly considered literature that is published by widely recognized scientific publishers or operations research journals.

Table 4.1: Terms used in literature search in combination with *freight transport network design modelling*.

Planning characteristics	**Sustainability characteristics**	**Modelling characteristics**
National planning	Emission constraints	Capacity expansion
Strategic planning	Emission costs	Infrastructure investment
Multi-modal	Minimize emissions	Arc flow
Multi-commodity	Decarbonization	Path flow
Multi-time period		Stochastic

When searching for literature regarding energy system modelling, we used the terms *energy system modelling* in conjunction with terms like *emissions* and *capacity investments*.

4.2 Freight Transport Modelling

Freight transport models have existed in the transport modelling literature since the 1960s, though the research at that time was focused on passenger transport [Tavasszy & de Jong, 2013]. During the 1970s demand for freight transport research grew and transport markets, and along with it, a demand for more advanced models. These models were used to gain insight into new market dynamics in a liberalized freight market in the UK, and to reduce the negative environmental impact of truck traffic [McKinnon, 2021]. From the 1980s and onward, much research has been done regarding the generation and evaluation of transportation service networks. This subfield of freight transport modelling, service network design, is mainly concerned with the selection and scheduling of services, the routing of goods and terminal operations [Andersen et al., 2009]. As new issues and considerations in the transport sectors appear, service network design models continually need to be modified and extended. A more recent modification includes a simultaneous determination of service networks and vehicle movements, denoted design-balanced capacitated multicommodity network design [Andersen et al., 2009]. Other recent service network design extensions consider CO_2 emissions, such as Sun & Lang [2015] and Bauer et al. [2010].

4.3 Planning Levels

Freight transportation models can generally be classified into one of three planning levels: strategic, tactical or operational [Crainic, 2000]. The operational level entails short-term planning, typically performed by the local management of a logistics service provider. This includes the day to day implementations and adjustments of schedules. This planning level also deals with dynamicity and stochasticity as it needs to answer to uncertain real-time requirements [Steadieseifi et al., 2014]. Operational models include Shiri et al. [2019] and Topaloglu & Powell [2007], both of which include stochastic elements. As our problem has little to do with operational planning, this is not discussed any further.

4.3.1 Tactical Planning

On a tactical level, medium term decisions are made. This involves optimally utilizing the given capacitated infrastructure. Relevant decisions include which transportation modes are to be used and how goods are moved and consolidated in the network [Steadieseifi et al., 2014]. Much work has been done in this field, including Crainic [2003], Nagurney [2010] and Demir et al. [2016]. The service network design problem, which already has been briefly discussed, is a type of tactical planning model. These problems can be divided into two subgroups of static and dynamic problems [Steadieseifi et al., 2014]. Static problems (Bektaş et al. [2010], Chang [2008]) assume that all problem aspects are unchanged over the time horizon, while in the dynamic models there is a time dimension which makes them discrete multi-period models. This allows dynamic models to represent many real-life properties of service network design problems, such as waiting time and transfers in terminals [Steadieseifi et al., 2014]. Examples of dynamic service network design models are Andersen et al. [2009], Bauer et al. [2010] and Andersen & Christiansen [2009]. Though most network design models are deterministic, some are stochastic and consider uncertainty in demand (Lium et al. [2009], Müller et al. [2021], Lo et al. [2013]), service time (Shiri et al. [2019]), or in both (Demir et al. [2016]).

4.3.2 Strategic Planning

The final planning level, strategic, is concerned with long-term decisions such as the design and evolution of infrastructure and constructing policies [Crainic, 2000]. This includes strategic planning at a international, national and regional level, from the perspective of governments and other policy makers. These types of models are often complex and consist of several modules which, for example, generate supply chains, calculate shipment sizes and frequencies, make choices on modes based on transport time and costs, and calculate the overall impact on the infrastructure networks [De Jong et al., 2013]. Strategic models also require large amounts of data for accurate depictions of the flow of goods in a country or region. The data is often gathered through combining multiple data sources, which is a complex task with a lot of associated uncertainty [Mjøsund et al., 2020]. National and international freight models can be said to be strategic due to their aggregated level and impact on national infrastructure planning and policy making. Nevertheless, they also incorporate tactical planning elements such as mode choice and allocation of flow [De Jong et al., 2013]. General strategic network design models that are not applied to a particular region or county include Guelat et al. [1990] and Crainic [2003].

National freight models have been developed for a number of European countries, including NGM (Caspersen et al. [2016]) and the similar Swedish Samgods Model (De Jong et al. [2010]). Both of these models have been used for various applications, including cost-benefit analysis, and in the Norwegian case, to develop the National Transport Plan [De Jong et al., 2013]. Both of these models employ an aggregate-disaggregate-aggregate (ADA) structure. This implies that commodity specific flows are disaggregated in a virtual firm-to-firm-flow, and the transportation of this flow is then optimized on a firm level where all firms want to minimize their costs. The shipments are then aggregated again over the firms in the same zone to an origin-destination-flow which is then assigned to transport mode. The national freight models for Norway and Sweden are static, i.e. they do not consider changes in the system over time, such as changes in infrastructure or in usage of fuels. In order to analyze the effect of changes to the system, a change must be added endogenously to the model and compared with a base-case through a cost-benefit analysis. This limits the benefit of static national models.

While the first iteration of NGM was a deterministic model, a later extension uses a random utility model which introduces some form of stochasticity [Caspersen et al., 2016]. While a firm's choice of transport mode and shipment size previously had been chosen only in a cost minimizing fashion, it now has a random element to more realistically model the firm's behaviour which is affected by many factors in addition to costs, such as reliability and flexibility of a transportation service. This model is still static, in the sense that it does not consider multiple time periods, and thus does not consider changes over time. A similar extension has been developed for the Swedish model as well [Abate et al., 2019].

National models have also been developed for other European countries, such as the NODUS model for Belgium (Pekin et al. [2009]) and the Basgoed (Significance et al. [2012]) and SMILE+ (De Jong et al. [2011]) models for the Netherlands. Though international models are less common, there have been developed freight models for the European Union such as Transtools (Burgess et al. [2006]) and Worldnet (Newton [2008]), where the latter also includes intercontinental transport. These models have been used by the European Commission to conduct cost-benefit analysis of infrastructure and pricing policies. Again, these models are static and do not directly model changes in the system over time.

4.4 Network Design

Based on the previous discussion we can categorize our model as network design model on a strategic planning level. In this subsection we present more model specific aspects of network design models.

4.4.1 Objective

Most transport network design models seek to minimize total costs as their objective, though what is included in the cost functions varies. Crainic [2000] describes a basic system with fixed costs that occur when utilizing an arc, as well as variable or utilization costs which are related to the volume of traffic on the arc. The total costs are minimized in what is denoted a fixed cost network design formulation. Guelat et al. [1990] also seek to minimize costs, though their concept of cost is more general, including delay and energy consumption as well as monetary costs. This is similar to Andersen et al. [2009], who include the total fixed costs and the time cost of both the transportation itself and waiting time. Andersen & Christiansen [2009] seek to maximize the profit from the perspective of a railway company while also accounting for important service quality factors, which is similar to cost minimizing models in its monetary focus. Other network design models seek to minimize more abstract metrics such as travel time (Shiri et al. [2019], Sharma & Mathew [2011]).

4.4.2 Emissions

Emission aspects can also be included in the objective in several ways. In many cases, emissions costs are included in a standard cost minimizing objective function, such as in Demir et al. [2016], Sun & Lang [2015] and in a suggested extension of Nagurney [2010]. Bauer et al. [2010] also include emissions in the objective, but in the form of the cost of energy consumption, which is a metric directly related to the GHG emissions of a transportation system. Luo et al. [2014] on the other hand proposes an incentive promotion rebate for arcs on environmentally friendly modes, i.e. railway and sea, as a means to promote modal shift. This is added to their total system cost objective function as a negative cost. Another way of including emissions in the objective of a model is to directly minimize the emissions. This is normally done in a bi-objective model, such as in Sharma & Mathew [2011], where the objectives are to minimize costs as well as emissions. Similar work has been done by Mostert et al. [2018] related to transportation in Belgium. The environmental aspect can also be included in a model formulation through emission constraints. This way of formulating the model will guarantee that a feasible solution meets specified emission reduction goals. Such a constraint is found in Chen & Kim [2018], where an emission constraint is applied on certain links to reduce urban pollution. This type of formulation is, however, not commonly found in strategic freight transport models.

4.4.3 Arc and Path Formulation

A network design model can be formulated with an arc or a path flow formulation. An arc flow formulation only has flow variables related to each arc in the network, while a path flow formulation has variables for flow on the possible paths. A path consists of a single arc or a sequence of arcs in the network. Crainic [2000] presents an arc flow based multi-commodity fixed cost network design formulation. In this type of formulation, the conservation of flow constraints are modelled by equating the demand of a product at a node to the total incoming minus the total outgoing arc flow of this product at the node. With N nodes and P products this leads to $N \cdot P$ number of conservation of flow constraints. A path formulation will lead to an exponential amount of path flow variables as the network grows, although only a few of the paths will carry flow in the optimal solution. Viable paths are for that reason generated as needed in order to decrease the size of the solution space instead of considering all possible paths [Mitchell, 2018]. The best paths can be generated through column generation or found with a heuristic.

Crainic [2000] presents an alternative path flow formulation for the multi-commodity fixed cost network design problem. The arc flow variable and parameters are connected to the path flow variables and parameters by an indicator function which is equal to one if the arc belongs to the path and zero otherwise. The conservation of flow can be modelled by simply ensuring that the total path flow of a product over all paths is equal to the total demand of the product. With P products, this results in P number of conservation of flow constraints. Most of the constraints that are related to the network design in the arc flow formulation is not needed in the equivalent path flow formulation, as they are addressed when paths are built. As seen, an arc formulation will often have a larger amount of constraints than a path formulation. Other benefits of a path flow formulation includes that it is more suitable when including transfers as the shift from one mode to another can be explicitly modelled in a path [Guelat et al., 1990]. Additionally, path flow formulation tends to lead to clearer visualization of results and easier adaption to algorithms than arc flow formulations [Guelat et al., 1990].

4.4.4 Modes

Freight transport models also differ in which modes of transportation are included. Most transportation models are multi-modal. This is especially common for models on a strategic planning level, as this is necessary in order to model intermodal transportation chains and transfer costs. These multi-modal models normally include road, rail and sea transport, and occasionally also inland water way and air. Uni-modal models also exists, where Bauer et al. [2010] and Andersen & Christiansen [2009] both model freight transport by rail and Lo et al. [2013] model freight transport on sea.

4.5 Relation to Energy System Modelling

Though capacity expansion investments and emission restrictions are often not considered directly in the field of strategic freight transportation network design, they are more common in other fields of operations research, such as energy system modelling. TIMES Norway (Rosenberg et al. [2020]) is a bottom-up energy system model on a national level that explicitly models decarbonization through considering sustainable fuels and allowing for investments in these over a long time horizon. The objective is to minimize system costs which includes investment costs as well as operational and maintenance costs. The model also poses restrictions on emissions and a limit of the growth in usage of new technologies, which is often not found in transport models. The TIMES modelling framework can be either deterministic or stochastic, where the stochastic version considers uncertainty in parameters such as weather-dependent renewable energy production and heat demand.

This is done in a two-stage modelling approach. Another energy system model that considers investments and emission restrictions is Heuberger et al. [2017]. We have drawn inspiration from this way of approaching the modelling of a national dynamic system. Combining elements from energy system modelling with freight transport modelling is part of our contribution in this thesis.

4.6 Classification of Related Literature

Freight transport modelling can be classified by the characteristics previously discussed. As seen in Table 4.2, a majority of the models we reviewed are tactical models and most of them seek to minimize total system costs. Multi-modal and multi-period models are also common, while we have found no models in the transport modelling field that consider emission caps. Emission costs are included in several models.

A categorization of the national and international freight transport models we have discussed is found in Table 4.3. Here, all models are strategic and multi-modal.

Table 4.2: An overview of related freight transport modelling literature. The papers marked with * are from energy system modelling literature. Objective: C = min costs, E = min emissions, T = min time, P = max profit, EM = equilibrium modelling. Emissions: Cost = emission costs, Obj = min emissions, Inc = incentives for low emission modes, Cap = emission cap. Modes: MM = multi-modal. Planning level: S = strategic, T = tactical, O = operational.

Paper	**Objective**	**Emissions**	**Modes**	**Planning level**	**Multi-period**	**Stochastic**
Crainic [2000]	C		MM	T	No	No
Guelat et al. [1990]	C		MM	S	No	No
Andersen et al. [2009]	C		Rail	T	Yes	No
Sun & Lang [2015]	C	Cost	MM	T	Yes	No
Shiri et al. [2019]	T			O	No	Yes
Topaloglu & Powell [2007]	C			O	Yes	Yes
Crainic [2003]	C	Cost	MM	O/T/S	Yes	No
Nagurney [2010]	C	Cost		T	No	No
Demir et al. [2016]	C	Cost	MM	T	Yes	Yes
Bektaş et al. [2010]	C			T	No	No
Chang [2008]	C&T		MM	T	No	No
Bauer et al. [2010]	C	Cost	Rail	T	Yes	No
Andersen & Christiansen [2009]	P		Rail	T	Yes	No
Lium et al. [2009]	C			T	Yes	Yes
Müller et al. [2021]	C		MM	T	Yes	Yes
Lo et al. [2013]	C		Sea	T	Yes	Yes
Luo et al. [2014]	C	Inc	MM	T	No	No
Sharma & Mathew [2011]	C&T		MM	T	No	No
Mostert et al. [2018]	C&E	Obj	MM	T	No	No
Chen & Kim [2018]	EM	Cap	MM	T	No	No
Rosenberg et al. [2020]*	C	Cost	MM	S	Yes	Yes
Heuberger et al. [2017]*	C	Cap		S	Yes	No
Our model	C	Cap	MM	S	Yes	Yes

Table 4.3: An overview of related literature regarding national and international freight transport models. IWW refers to inland waterways.

Model	**Source**	**Area**	**Modes**
NGM	Caspersen et al. [2016]	Norway	Road, rail, sea, air
Samgods	De Jong et al. [2010]	Sweden	Road, rail, sea, air
NODUS	Pekin et al. [2009]	Belgium/Europe	Road, rail, IWW
Basgoed	Significance et al. [2012]	The Netherlands	Road, rail, IWW
SMILE+	De Jong et al. [2011]	The Netherlands	Road, rail, sea, air, IWW
Transtools	Burgess et al. [2006]	EU	Road, rail, sea, IWW
Worldnet	Newton [2008]	EU	Road, rail, sea, air, IWW

4.7 Research Contribution

For our model we take on the perspective of a national government policy maker. This enables options to make investments in infrastructure and entails considering the development in fuel costs, technology development and carbon prices. This perspective, along with the long-term time horizon, makes it natural to classify our model as strategic. Like many other national freight models, we also include elements of tactical freight modelling, such as designing a service network and assigning flow to arcs. As we want to model Norwegian freight transport, which today is mainly performed by road, sea and rail, our model will be multi-modal, with these modes included. We include stochasticity in our model to account for the uncertainty in future availability of sustainable fuels. When making decisions under uncertainty, the decision that is made today should be balanced against the conditions we might face tomorrow so that we always will end up in a decent position no matter the realization of the uncertainty. In our case, a stochastic model allows us to take into account new information about fuel maturity as this becomes available, and make decisions today which gives us the opportunity to adapt to the future realization of maturity levels. While there are other network design model that are stochastic, these focus on uncertainty in demand or in service time. We can categorize our problem as a stochastic strategic multi-modal freight transportation network design problem.

In our model, we use emission constraints to explore scenarios where the emission reduction goals of Norway are met. Emission reductions are achieved through gradually transitioning towards using mode-fuel combinations with little to no GHG emissions. Emission costs are also a part of our objective function, through the carbon price included in the cost of using a specific mode-fuel combination. To the best of our knowledge, including emission constraints and the possibility of using multiple mode-fuel combinations, has not yet been done in strategic transportation modelling.

Adding elements found in energy system modelling to our freight transport model formulation is also an original contribution. This enables a multi-time period perspective of how infrastructure should optimally develop under continuously stricter emission constraints. Elements from energy system modelling such as maturity limits for new technologies and time dependent investment opportunities are highly relevant for our problem context. We have not, to the best of our ability, found any previous research that combines these aspects of transport modelling and energy system modelling.

Chapter 5

Methodology

In this chapter, we present the methodology in terms of representing the problem as a stochastic mixed integer program (SMIP) and the progressive hedging solution method with references to relevant literature. We introduce stochastic programs with its notation as well as scenario trees in order to visualize the problem. Solving the extensive form of a mixed integer stochastic program may be computationally exhausting as a substantial number of scenarios can yield extremely large SMIPs. Progressive hedging, a scenario-based decomposition algorithm, is presented as an alternative solution method, as it is capable of solving large-scale SMIPs efficiently.

5.1 Stochastic Programming

When we do not have perfect information about all parameters included in the objective function or the constraints of an optimization model, we are faced with decision making under uncertainty. A stochastic program (SP) is a mathematical model that takes this uncertainty and its probability distribution into account. The SP can contain several decision stages. A stage in this setting is defined as a moment in time where decisions can be made after the revelation of new information. The decision variables are defined for each of these stages. For the two-stage problem, the decision variables are divided into first-stage and second-stage variables. In most cases the first-stage decisions are determined before information about the uncertain parameters are realized. On the other hand, the second-stage decisions are made after the realization of the uncertainty. Consequently, the decisions made in the second-stage capture the opportunity to take new information into account and adapting to this. This gives the solution some flexibility which is usually not captured in a deterministic framework. When the pattern of observing and deciding is repeated multiple times, we obtain a multi-stage problem; a generalization of the two-stage problem. In this thesis, we formulate a multi-stage stochastic program, which we apply to our case study in a two-stage manner.

A standard two-stage stochastic minimization problem has the following general structure [Gade et al., 2016]:

$$\min \quad c^\top x + E[h(x, \tilde{\xi})] \tag{5.1}$$

$$\text{s.t.} \quad Ax \geq b \tag{5.2}$$

$$x \in \mathbb{Z}_+^{p_1} \times \mathbb{R}^{n_1 - p_1} \tag{5.3}$$

where

$$h(x,\xi) = \min \quad g(\xi)^\top y \tag{5.4}$$

$$\text{s.t.} \quad Wy \geq r(\xi) - T(\xi)x \tag{5.5}$$

$$y \in \mathbb{Z}_+^{p_2} \times \mathbb{R}^{n_2 - p_2}. \tag{5.6}$$

The domains of the parameters are: $c \in \mathbb{R}^{n_1}, A \in \mathbb{R}^{m_1 \times n_1}, b \in \mathbb{R}^{m_1}, g \in \mathbb{R}^{n_2}, W \in \mathbb{R}^{m_2 \times n_2}, T \in \mathbb{R}^{m_2 \times n_1}$ and $r \in \mathbb{R}^{m_2}$. In this problem, x is a vector of first-stage decision variables with c as its objective coefficient vector, and $g(\xi)$ is the objective coefficient vector of the second stage variables y. As seen from constraints (5.3) and (5.6), both the first and second-stage variable vectors consists of integers and continuous variables. The uncertain data is represented by $\tilde{\xi}$. When the probability distribution is discrete ξ becomes a discrete random variable with possible realizations equal to the number of scenarios $|\Xi|$. The objective in (5.1) is to minimize the first-stage costs and the expected second-stage costs. The first-stage decisions are restricted by constraints (5.2), while the second-stage decisions are restricted by constraint (5.5). From this constraint it is seen that the first-stage decisions constrain the second-stage decisions through the technology matrix $T(\xi)$.

In the case of a finite number of realizations ξ of $\tilde{\xi}$, an extensive form of the scenario formulation (EFS) can be formulated. The EFS is obtained by explicitly presenting the SP in its full form by considering each of the possible scenarios. An EFS of the SP is defined in (5.1) - (5.5) [Gade et al., 2016]:

$$\min \quad \sum_{\xi \in \Xi} p_\xi (c^\top x(\xi) + g(\xi)^\top y(\xi)) \tag{5.7}$$

$$\text{s.t.} \quad Ax(\xi) \geq b, \qquad \xi \in \Xi \tag{5.8}$$

$$T(\xi)x(\xi) + Wy(\xi) \geq r(\xi), \qquad \xi \in \Xi \tag{5.9}$$

$$x(\xi) - \hat{x} = 0, \qquad \xi \in \Xi \tag{5.10}$$

$$\hat{x}, x(\xi) \in \mathbb{Z}_+^{p_1} \times \mathbb{R}^{n_1 - p_1}, \qquad \xi \in \Xi \tag{5.11}$$

$$y(\xi) \in \mathbb{Z}_+^{p_2} \times \mathbb{R}^{n_2 - p_2}, \qquad \xi \in \Xi. \tag{5.12}$$

In the formulation above, separate first stage variables have been introduced for each scenario with explicitly defined *non-anticipativity* constraints. These constraints are given by 5.10 and ensure that the first-stage solutions are equal across the different scenarios.

The uncertainty in a SP can be visualized by a scenario tree. Each scenario represents a path from the root to a leaf of the scenario tree. The path contains information about the manner in which the stochastic elements develop over the time periods in the problem [Higle, 2005]. An individual scenario can be considered a deterministic optimization problem itself. The example of an scenario tree in Figure 5.1 consists of nodes and branches.

In a two-stage SP branching only occurs when the uncertain data is realized. It can be seen from the scenario tree example that this branching happens after 2025, which leads to eight possible realizations for the next time periods. The two nodes for the first time periods before the initial branching, 2022 and 2025, belongs to the root, while the rest of the nodes are defined as leaf nodes. This is the scenario tree of the main scenario structure we consider in our computational study.

The decision variables that are associated with the scenarios that pass through the same node in the scenario tree must hold identical values, as they share the same history of information. This leads to the need for non-anticipativity constraints as explained above, which must hold for all non-leaf nodes in the scenario tree. In the two-stage case, they must hold for the solutions in the root nodes.

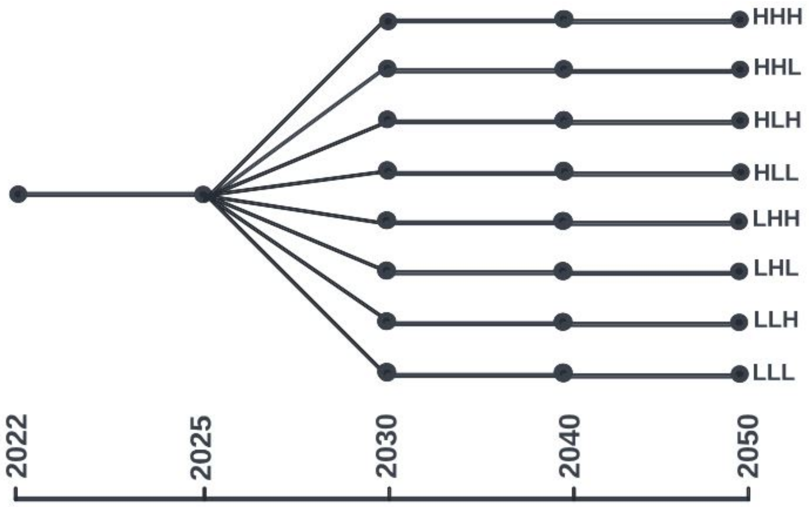


Figure 5.1: A two-stage scenario tree with branching in 2025 and eight possible scenarios for the second stage time periods 2030, 2040 and 2050.

To quantify potential benefits of a stochastic approach when modelling a problem, the value of the stochastic solution (VSS) is often used. VSS measures how much we can expect the objective value to improve on average if we use stochastic programming instead of a deterministic approach. For a minimization problem the VSS is calculated as the difference between the expected result of the expected value solution (EEV) and the result of the SP. A SP is often called the recourse problem (RP) in literature, as the second stage decisions are made in order to take recourse action after the uncertain data is realized.

The EEV is found by solving the expected value (EV) problem and evaluating its first-stage solution in the SP. In the EV problem, all of the uncertain data is replaced by its expected values and the deterministic program is solved [Birge, 1982]. The EEV then becomes the expected cost when using the EV problem's first-stage solutions. VSS can then be calculated as:

$$VSS = EEV - RP \tag{5.13}$$

.

When the first stage and/or the second stage variables contain both continuous and integer variables, the problem is a stochastic mixed integer program (SMIP). In this thesis the model is a SMIP, with both binary and continuous variables in the first and second stage, as we seek to model both investments and flow of goods. When integer variables are a part of the formulation, it is of interest to calculate the relative gap between the primal objective bound and the dual objective bound. The primal objective bound is the value of the currently best feasible solution in an iterative process. The dual objective bound is the current best solution in an iteration of the problem, with some or all integer restrictions removed. In a minimization problem, the primal objective bound is an upper bound, while the dual objective bound is a lower bound. The optimality gap is often reported as the MIPGap by general-purpose solvers. Large-scale SMIPs might be time consuming to solve, so alternative solution methods beside solving the EFS directly should be considered. A solution method that is capable of solving stochastic programs with mixed integers in both first and second stage is the progressive hedging algorithm.

5.2 Progressive Hedging Algorithm

The progressive hedging algorithm (PHA) is scenario-based decomposition strategy for stochastic programming. The standard PHA is presented in Rockafellar & Wets [1991]. It was originally developed for formulations containing only continuous variables, but has later been successfully applied as a heuristic solution procedure for SPs with integer variables in both stages [Watson & Woodruff, 2011].

The general outline of the progressive hedging algorithm (PHA) is that non-anticipativity constraints are relaxed, and the objective function coefficients of the scenario subproblems are updated in each iteration to reflect the costs of non-anticipativity. This costs is based on the distance between the current solution and a non-anticipative, aggregated solution. The aggregated solution is the average solution over all scenario solutions [Aasgård & Skjelbred, 2020].

The complete progressive hedging algorithm for two stage SMIPs is presented in Algorithm 1. This formulation is based on Gade et al. [2016].

Algorithm 1 The Progressive Hedging Algorithm for Two-Stage SMIPs

1: **Initialization**: $\nu \leftarrow 0$ and $\omega^{\nu}(\xi) \leftarrow 0, \forall \xi \in \Xi$. For each $\xi \in \Xi$, compute:

$$(x^{\nu+1}(\xi), y^{\nu+1}(\xi)) \in \arg\min_{(x,y)\in X(\xi)} c^{\top}x + g(\xi)^{\top}y$$

2: **Iteration Update**: $\nu \leftarrow \nu + 1$

3: **Aggregation**: $\hat{x}^{\nu} \leftarrow \sum_{\xi\in\Xi} p_{\xi} x^{\nu}(\xi)$

4: **Price Update**: $\omega^{\nu}(\xi) \leftarrow \omega^{\nu-1}(\xi) + \rho(x^{\nu}(\xi) - \hat{x}^{\nu})$

5: **Decomposition**: For each $\xi \in \Xi$, compute:

$$(x^{\nu+1}(\xi), y^{\nu+1}(\xi)) \in \arg\min_{(x,y)\in(\xi)} \{c^{\top}x + g(\xi)^{\top}y + \omega^{\nu}(\xi)^{\top}x + \frac{\rho}{2}\|x - \hat{x}^{\nu}\|^2\}$$

6: **if** all scenario solutions $x(\xi)$ are equal **then**

7: Stop.

8: **else**

9: Go to step 2.

In the initialization step, Step 1, the individual scenario problems are solved. The iteration count is then updated in Step 2. In the aggregation step, Step 3, the individual scenario first-stage solutions are aggregated to an average solution. The dual prices of non-anticipatvity are then updated in Step 4 by adding the distance between the current first-stage solution and the aggregated solution times an external punishment parameter ρ. The decomposition step, Step 5, solves the individual scenario problems with a modified first-stage cost with the dual prices added and a quadratic term of the squared two-norm of the distance between the a new solution and the aggregated solution of the current iteration. If all first-stage scenario solutions are equal, we have reached convergence. If not, the next iteration starts at Step 2.

In this thesis, the PHA is implemented using the mpi-sppy support framework for solving SPs in Python [mpi, 2020].

A limitation to the PHA is the lack of information the it provides with regards to solution quality relative to the optimal objective function value [Gade et al., 2016]. Without information on lower bounds, the PHA only serves as a high-quality heuristic. Computing upper and lower bounds during every iteration of the PHA makes it possible to obtain a feasible solution and terminate based on the convergence gap obtained from these bounds. In the next sections we present the upper and lower bounding procedures that are used with the PHA within the mpi-sppy framework.

5.2.1 Obtaining Upper and Lower Bounds

The upper bounds are computed from a feasible solution. If the PHA has fully converged, and not terminated because of a time or iteration limit, a feasible solution can be obtained directly from the algorithm. However, if we want to estimate optimality gaps and terminate early with a feasible solution that satisfies the integer and non-anticipativity restrictions, an additional heuristic must be implemented [Knueven et al., 2020]. One type of heuristic that can be used is what is called "xhat-specific" in the mpi-sppy framework. For a two-stage problem, the general outline of the algorithm can be summarized as follows: values of a single scenario subproblem serve as a candidate solution, and the stochastic program is solved for the other subproblems using the candidate solutions first-stage values to obtain an objective function value, which is the upper bound. According to Knueven et al. [2020], scenario sub-problem solutions can be especially effective when integer restrictions make it unlikely that the aggregation of scenario solutions will be feasible. The algorithm can be improved by looping over a number of scenarios, instead of just using one, until an iteration from the PHA is finished. The best bound that was calculated is reported as the upper bound. This is called the "xhat-looper", and is what we use to obtain feasible solutions and upper bounds in parallel to the PHA.

Gade et al. [2016] demonstrate that the dual prices of the non-anticipativity constraints, $\omega(\xi)$, define implicit lower bounds for the PHA. These dual prices are obtained from the PHA and a lower bound, $D(\omega)$, is computed based on the following proposition with the notation introduced in Section 5.1:

Let $\omega = (\omega(\xi))_{\xi \in \Xi}$, where $\omega(\xi) \in \mathbb{R}^{n_1}$ satisfy $\sum_{\xi \in \Xi} p_\xi \omega(\xi) = 0$. Let

$$D_\xi(\omega(\xi)) := \min_{(x,y) \in \mathcal{X}(\xi)} \Big(c^\top x + g(\xi)^\top y + \omega(\xi)^\top x \Big). \tag{5.14}$$

Then

$$D(\omega) := \sum_{\xi \in \Xi} p_\xi D_\xi(\omega(\xi)) \leq z^*. \tag{5.15}$$

Gade et al. [2016] provides a proof that this is a valid lower bound under the assumption that the SMIP is feasible and has an optimal solution with $-\inf < z* < +\inf$, where z* is the optimal objective function value. It is also assumed that $X(\xi) \neq 0, \forall \xi \in \Xi$. This proof is listed in Appendix A.

Chapter 6

Problem Description

Modelling a country's transportation system entails the allocation of flow of goods between zones to forms of transportation. A form of transportation is defined as a combination of mode, fuel, and vehicle. The transportation system is modelled from a system perspective, taking on the role as a body of government seeking to minimize costs overall while complying with emission targets. The rate at which new sustainable fuel technologies become available, i.e. their maturity level, is uncertain. This problem context results in a stochastic multi-modal, multi-commodity modelling problem that extends over multiple time periods. We can define the problem as a strategic network design problem.

In each time period, freight has to be assigned to a form of transportation in such a way that all demand is fulfilled. A time period is defined as a year, though consecutive time periods do not need to be consecutive years. We only consider demand and flow of goods between zones, and not last-mile delivery or transport within a zone. Demand is defined as the number of tonnes of a product group that is to be delivered from an origin zone to a destination zone in a time period. A mode is a means of transportation between any two zones, and the modes considered are road, sea and rail. A fuel refers to the source of energy used on a mode, which includes diesel, battery electricity and hydrogen among other fuels. A vehicle refers to a specific type of truck, ship or train, and are thus mode specific. The vehicles have different capacities and can carry different product groups. Each possible form of transportation, i.e. each combination of mode, fuel and vehicles, has an associated generalized cost and emission factor per tonne transported. Not all combinations of mode and fuel are possible, though all vehicles within a mode can use all fuels possible for that mode. Also, all product groups can be transported by every mode, but only by one vehicle within each mode. Hence, the vehicle used is determined by the product group that is to be transported.

The objective is to minimize the present value of the system costs, which includes generalized transportation costs, transfer costs, capacity expansion costs and energy station costs. The generalized transportation costs are dependent on the distance and weight of transported goods, as well as the form of transportation used. Both monetary and non-monetary costs are included, such as fuel costs, carbon prices, driver or crew wages and vehicle costs. The freight transportation system is intermodal, meaning that goods can be moved from one mode to another along the way from its origin to its destination. The activity of transferring goods from one mode of transportation to another is time and labour consuming. Therefore, transfers have an associated cost dependent on the amount of goods transferred and which modes that are involved in the transfer.

There are limitations on how much the modes and fuels can be used. Freight transport on rail is restricted both by limited capacity in the rail infrastructure, as well in the railway terminals. Freight transport at sea is restricted by the capacity in harbours. Fuels have associated restrictions related to the maturity of the fuel. This maturity level, which encompasses both the technical maturity and scalability of a fuel, restricts the number of tonnes that can be transported using a fuel technology in a time period for a certain mode. The maturity level of a fuel in a time period is uncertain. Also, the usage of a new fuels on all modes is restricted by the energy station network, as fueling and charging stations have to be built in harbours, railway terminals and on road stretches to allow for the fuel to be used on certain arcs. The capacity for a mode or fuel can be expanded through capacity increasing investments. To allow for greater usage of a mode, capacity can be increased in harbours and railway terminals in a zone or on railway lines between two zones. For fuels, investments in charging and filling infrastructure in harbours and railway terminals, and on roads between zones, will enable more tonnes to be transported by the fuel. Additionally, a non-electrified railway line can be upgraded to a partial or fully electrified line, making respectively battery and CL-trains possible to utilize. All investments must be done in the time period before the added capacity or upgraded railway line can be utilized, thus no investments will be made in the final time period.

We consider a time horizon until 2050 when countries should be climate-neutral according to the Paris Agreement. The time horizon is divided into discrete regular time periods, so that it captures the gradual maturing of sustainable fuels and phasing out of fossil fuels. The total yearly emissions from the transportation system is constrained to a certain limit in each time period.

The purpose of the model is to explore possible future developments in usage of sustainable fuels and infrastructure investments. The objective is to minimize the total costs of the national transportation system considering long-haul transportation. The decisions that are to be made are which forms of transportation that are to be used to fulfill all demand in each time period, as well as which infrastructure investments are needed to achieve the necessary capacities. This should be done while complying with the existing capacities in the network, as well as the constraints on emissions which are decided by the government.

Chapter 7

Mathematical Model

In this chapter we present our mathematical model. First, we present our modelling choices in 7.1, before the notation of our mathematical formulation is introduced in the following sections. All necessary sets and indices are presented in Section 7.2. Then we outline all relevant parameters in Section 7.3 and define continuous and binary variables in Sections 7.4 and 7.5 respectively. The full model formulation is provided in Section 7.6. Then, finally, an overview of the path generation method used in given in Chapter 7.7.

7.1 Modelling Choices

In this section we provide a brief motivation for our overarching modelling choices. This includes how the network is represented in terms of arcs and paths, the choice of a two-stage model formulation, how capacity expansions are modelled, the role of non-anticipativity constraints and how the emission contraint can be relaxed.

7.1.1 Arcs, Modal Links and Paths

We want to capture flow of a specific mode-fuel combination, as well as total flow on the mode used between two nodes. To achieve this arcs are defined as directed and fuel-specific. Various arcs adhere to the same modal link which reflects the physical infrastructure of the mode in use. Thus, modal links are only defined by mode and are undirected. The total flow of all arcs that adhere to a modal link equals the flow of the modal link. Figure 7.1 provides a more detailed description of the relation between arcs and modal links. Defining modal links makes it simple to capture and increase capacity on a given road, rail or sea link.

(a) Three possible modal links.

(b) Eight corresponding arcs.

Figure 7.1: An example network showing the difference between modal links and arcs. Two nodes are directly connected by sea, rail and road, and thus have three modal links. This leads to eight total arcs as two fuels are available on road and flow goes in both directions.

A path formulation is chosen over an arc formulation to achieve a model that is more easily solved by only considering a limited number of paths. Additionally, defining a path as a set of modal links instead of as a set of arcs reduces computational complexity drastically. This means paths are defined only by the mode(s) used, so a unique path is not needed for every mode-fuel combination. A disadvantage of this approach is that there is no way to observe which fuels are used on specific paths. We can only observe the flow of different mode-fuel combinations on the underlying arcs that connect to the path. However, we find that the benefits of a reduced set of paths outweigh this information loss, as we do not need detailed insight into which paths use which fuels for our model formulation.

7.1.2 Two-Stage Stochastic Model Formulation

The planning horizon is split into discrete time periods. This way of representing time is beneficial since it is simple to implement and as much of our data is only available for certain regular time periods. As we are faced by uncertain technology maturities, we choose to model a two-stage formulation in which maturity development of fuels is uncertain until a specific time period. The first-stage variables are defined by all of the system's decisions that are made until this specific time period. The second-stage variables are given by the same type of decisions, but after this specific time period when the uncertain data is realized. There is also potential to model this problem as a multi-stage formulation where only the maturity of the subsequent time period is realized. While the current focus is on a two-stage approach, the model formulation is generalized to also apply for the multi-stage version.

7.1.3 Modelling of Capacity Expansion

Capacity expansions in terminals and modal links are modelled as step-wise investments, to reflect a realistic expansion of such infrastructure. Binary variables are used to ensure that additional capacity can only be exploited if an investment costs has incurred. The amount of times a "step" can be made in available capacity, may vary and can not exceed the amount of time periods of the problem. Expanding capacity of charging infrastructure of an arc is modelled linearly, as these investment are of a smaller scale and can happen gradually. The price of adding charging or filling capacity is approximated to a linear cost in NOK/tonnes.

7.1.4 Non-Anticipativity Constraints

In order to obtain solutions that are implementable, non-anticipativity constraints must be included in the model formulation. The constraints can be included in several ways. In this model formulation, the set of non-anticipativity constraints are formulated similar to what was presented by Higle [2005]:

$$N^{ST} = \{\{x_\xi\}_{\xi \in \Xi} | x_{t(n),\xi} - x_n = 0, \forall \xi \in B(n), \forall n \in N^{ST}\} \tag{7.1}$$

For all non-leaf nodes $\mathcal{N}^{\mathcal{ST}}$ in a scenario tree, there is a set of scenarios $\mathcal{B}(n)$ that pass through. This formulation imposes that the decision variables of these scenarios must be equal in the stage, $t(n)$, of the node n, by the use of the auxiliary variables x_n. The auxiliary variables will not be defined explicitly in the model formulation, but they are shown in the non-anticipativity constraints. Note that in the case of a two-stage problem formulation, all scenarios pass through the same non-leaf nodes.

7.1.5 Relaxing Emission Constraints

The emission constraints are relaxed with an associated penalty for violation in the objective function. This modelling choice makes it possible to ensure feasibility and to calculate VSS values. Hard constraints can lead to an infinitely high VSS because the model used to calculate EEV may become infeasible, even if the EV problem is feasible. Relaxing the emission constraint makes it possible to evaluate the need for a stochastic approach, but the penalty parameter will affect the magnitude of the VSS [Wallace, n.d.].

7.2 Sets and Indices

$\mathcal{T}$ = Set of time periods or stages, indexed by t and τ.
$\mathcal{P}$ = Set of product, indexed by p.
$\mathcal{M}$ = Set of modes, indexed by m.
$\mathcal{N}$ = Set of nodes, indexed by i, j.
Ξ = Set of scenarios, indexed by ξ.
$\mathcal{N}^{ST}$ = Set of nonleaf nodes in the scenario tree, indexed by n.
$\mathcal{N}_t^{ST}$ = Set of nonleaf nodes in the scenario tree in stage t, indexed by n.
$\mathcal{B}_n$ = Set of scenarios that pass through the nonleaf node n, indexed by ξ.
$\mathcal{T}^{NL}$ = Set of stages in the scenario tree where there exist nonleaf nodes, indexed by t.
$\mathcal{OD}$ = Set of all origin and destination node pairs where demand for transportation exists (OD pairs), indexed by o, d.
$\mathcal{R}$ = Set of routes, indexed by r.
$\mathcal{L}$ = Set of modal links, which are undirected links between two nodes i and j with mode m on route r, indexed by l.
$\mathcal{L}^{DIR}$ = Set of directed modal links between two nodes i and j with mode m on route r, indexed by l.
$\mathcal{L}^{CAP}$ = Subset of modal links l that are constrained by a certain capacity.
$\mathcal{S}_m$ = Set of possible terminal types for mode m, indexed by s.
$\mathcal{P}_s$ = Set of product groups that can be processed at terminal type s, indexed by p.
$\mathcal{L}^{UPG}$ = Subset of $\mathcal{L}^{CAP}$ where the infrastructure of modal link l can be upgraded to allow for flow of more fuels.
$\mathcal{F}$ = Set of fuels and technologies, indexed by f.
$\mathcal{F}_l$ = Set of allowed fuels f on link l.
$\mathcal{F}_l^{UPG}$ = Set of fuels f which are only allowed on certain upgraded variants of a modal link l.
$\mathcal{A}$ = Set of directed arcs, indexed by a, where $a = (i, j, m, f, r)$ is defined from node i to node j with mode m and fuel f on route r.
$\mathcal{A}_{lf}^{PAIR}$ = Pair of arcs a in both directions where fuel f is used on a modal link l.
$\mathcal{A}_a^{PAIR}$ = Pair of arcs a' in both directions given an arc a.
$\mathcal{A}_{mf}$ = Set of arcs a for a specific mode m and fuel f.
$\mathcal{A}^{Ch}$ = Subset of arcs a that are eligible for charging or filling infrastructure.
$\mathcal{A}_l$ = Set of all arcs that belong to a directed modal link l.
$\mathcal{K}$ = Set of paths, indexed by k.
$\mathcal{K}_{od}$ = Set of paths that lead from origin o to destination d.
$\mathcal{K}_{im}^{o}$ = Set of all paths originating from node i with mode m.
$\mathcal{K}_{im}^{d}$ = Set of all paths ending in node i with mode m.
$\mathcal{K}_{im}^{Tr}$ = Set of all paths with a transfer in node i to or from mode m.
$\mathcal{MM}$ = Set of all types of transfer between two modes, indexed by mm.
$\mathcal{K}_{mm}^{Tr}$ = Set of all transfer paths containing the transfer type mm.
$\mathcal{NM}^{CAP}$ = Set of all domestic terminals (nodes) i and mode m combinations with capacity constraints.
$\mathcal{MF}^{NEW}$ = Set of all mode m and fuel f combinations which are not technologically mature.
$\mathcal{U}_f^{FUEL}$ = Set of upgrades u that allow for fuel f.
$\mathcal{U}_l^{LINK}$ = Set of possible upgrades u for modal link l.

7.3 Parameters

Q_{odpt} = Demand for transport of product p from origin o to destination d in time period t in tonnes.
C^{GEN}_{apt} = Generalized cost of transporting one tonne of product p, using arc a in time period t in NOK/tonnes.
C^{Tr}_{mmp} = Transfer costs related to transfer type mm for product p in NOK/tonnes.
C^{LINK}_{l} = Cost of an investment in infrastructure which leads to an increase in capacity at a modal link l in NOK.
C^{UPG}_{lu} = Investment cost of upgrading a modal link l to upgrade type u in NOK.
C^{NODE}_{ims} = Investment cost of increasing the capacity in terminal type s at node i for mode m in NOK.
C^{Ch}_{a} = Cost of increasing charging or filling capacity for arc a in NOK/tonnes.
$C^{Penalty}$ = Cost of violating the emission limit in NOK/gCO2.
$Y^{BASE,l}_{l}$ = Initial capacity for modal link l in tonnes.
Y^{LINK}_{l} = Additional capacity from investing in infrastructure to increase the capacity of a modal link l in tonnes.
MAX^{LINK}_{l} = Maximum amount of times investments can be made in a modal link l.
$Y^{BASE,n}_{ims}$ = Initial capacity for terminal type s for mode m in node i in tonnes.
Y^{NODE}_{ims} = Additional capacity from investing in infrastructure to increase the capacity of terminal type s for mode m in node i in tonnes.
MAX^{NODE}_{ims} = Maximum amount of times investments can be made in terminal type s for mode m in node i.
$Y^{BASE,Ch}_{a}$ = Initial capacity of an arc a that is eligible for charging or filling infrastructure in tonnes.
E_{apt} = Emission factor in gCO_2 per tonne of freight transport over arc a for product p in time period t.
$CO2^{CAP}_{t}$ = CO_2 emission limit for time period t in gCO_2.
$Y^{TECH}_{mft\xi}$ = Maturity limit of using fuel f on mode m in time period t for scenario ξ .
J_{lk} = Binary parameter, 1 if modal link l is present in path k, 0 otherwise.
δ_t = Discount factor for period t.
M_l = Sufficiently large number (big M) for each modal link l.
p_ξ = Probability assigned to scenario ξ.

7.4 Continuous Variables

$x_{apt\xi}$ = Flow of product p transported over arc a in time period t for scenario ξ in tonnes.
$h_{kpt\xi}$ = Flow of product p on path k in time period t for scenario ξ in tonnes.
$y^{charge}_{at\xi}$ = Capacity increase of arcs a that are eligible for charging or filling infrastructure in time period t for scenario ξ in tonnes.
$v_{t\xi}$ = Emission violation in time period t for scenario ξ in tonnes CO_2.

7.5 Binary Variables

$z^{upg}_{lut\xi}$ = 1 if investment in upgrade u at modal link l occurs at time period t for scenario ξ, 0 otherwise.
$z^{link}_{lt\xi}$ = 1 if a capacity investment at modal link l occurs at time period t for scenario ξ, 0 otherwise.
$z^{node}_{imst\xi}$ = 1 if a capacity investment in terminal type s for mode m in node i occurs at time period t for scenario ξ, 0 otherwise.

7.6 Model Formulation

In this section, we present our mathematical model using the nomenclature provided. The objective function contains the total costs of the transportation system and is minimized over all of the time periods. The objective is given by (7.2):

$$\begin{aligned}\min \quad & \sum_{\xi\in\Xi}\sum_{t\in\mathcal{T}} p_\xi \delta_t \Big[\sum_{p\in\mathcal{P}}\sum_{a\in\mathcal{A}} C^{GEN}_{apt} x_{apt\xi} + \sum_{p\in\mathcal{P}} \sum_{mm\in\mathcal{MM}} \sum_{k\in\mathcal{K}^{Tr}_{mm}} C^{Tr}_{mmp} h_{kpt\xi} \\ & + \sum_{l\in\mathcal{L}^{UPG}} \sum_{u\in\mathcal{U}^{LINK}_l} C^{UPG}_{lu} z^{upg}_{lut\xi} + \sum_{l\in\mathcal{L}^{CAP}} C^{LINK}_l z^{link}_{lt\xi} \\ & + \sum_{(i,m)\in\mathcal{NM}^{CAP}} \sum_{s\in\mathcal{S}_m} C^{NODE}_{ims} z^{node}_{imst\xi} + \sum_{a\in\mathcal{A}^{Ch}} C^{Ch}_a y^{charge}_{at\xi} + C^{Penalty} v_{t\xi} \Big]\end{aligned} \tag{7.2}$$

The objective function has seven terms reflecting the way costs are incurred in the network. The first term captures the generalized costs of transporting the total flow of goods over all arcs, with carbon prices included. These costs are dependent on the arc, product group, and time period, as they vary with mode, fuel, distance, vehicle type (product group) and over time. The second term captures the transfer costs related to flow on intermodal paths for the different product groups and types of transfer between modes. The third term consist of one-time investment costs of upgrading the existing infrastructure on modal links that are suitable for upgrades. The fourth term captures the one-time investment costs in infrastructure which lead to step-wise increase in capacity at a modal link. The fifth term captures the investment costs of expanding capacities at capacitated terminals. The cost of linearly expanding the charging or filling infrastructure at an arc is given by the sixth term. This cost is calculated based on the costs of the filling or charging stations needed to fulfill the expanded capacity. The last term consists of the emission limit violation penalty.

$$\sum_{k\in\mathcal{K}_{od}} h_{kpt\xi} = Q_{odpt}, \qquad (o,d)\in\mathcal{OD}, p\in\mathcal{P}, t\in\mathcal{T}, \xi\in\Xi \tag{7.3}$$

$$\sum_{a\in A_l} x_{apt\xi} = \sum_{k\in\mathcal{K}} J_{lk} h_{kpt\xi}, \qquad l\in\mathcal{L}^{DIR}, p\in\mathcal{P}, t\in\mathcal{T}, \xi\in\Xi \tag{7.4}$$

The objective function is subject to a number of constraints. Constraint (7.3) ensures that the total product flow over all paths between two nodes are equal to the demand Q_{odpt} of transportation of said product between the two nodes for all time periods. Constraint (7.4) connects arc and path flow by ensuring that the total arc flow on a link is equal to the path flow on paths that pass through this link. The binary indicator function J_{lk} is used to validate if a modal link is a part of a path.

$$\sum_{p \in \mathcal{P}} \sum_{f \in \mathcal{F}_l} \sum_{a \in \mathcal{A}_{lf}^{PAIR}} x_{apt\xi} \leq Y_l^{BASE,l} + Y_l^{LINK} \sum_{\tau < t} z_{l\tau\xi}^{link}, \qquad l \in \mathcal{L}^{CAP}, t \in \mathcal{T}, \xi \in \Xi \tag{7.5}$$

$$\sum_{t \in \mathcal{T}} z_{lt\xi}^{link} \leq MAX_l^{LINK}, \qquad l \in \mathcal{L}^{CAP}, \xi \in \Xi \tag{7.6}$$

$$\sum_{p \in \mathcal{P}} \sum_{a \in \mathcal{A}_{lf}^{PAIR}} x_{apt\xi} \leq M_l \sum_{\tau < t} \sum_{u \in \mathcal{U}_f} z_{lu\tau\xi}^{upg}, \qquad f \in \mathcal{F}_l^{UPG}, l \in \mathcal{L}^{UPG}, t \in \mathcal{T}, \xi \in \Xi \tag{7.7}$$

$$\sum_{p \in \mathcal{P}} \sum_{a' \in \mathcal{A}_a^{PAIRS}} x_{a'pt\xi} \leq Y_a^{BASE,Ch} + \sum_{\tau \leq t} y_{a\tau\xi}^{charge}, \qquad a \in \mathcal{A}^{Ch}, t \in \mathcal{T}, \xi \in \Xi \tag{7.8}$$

The capacity of certain links and terminals is constrained, but a certain amount of capacity expansion is possible. Constraint (7.5) limits the total flow of goods to $Y_l^{BASE,l}$ on a capacitated modal link. Additional capacity, Y_l^{LINK}, can be added through step-wise investments in infrastructure. Constraint (7.6) puts an upper limit MAX_l^{LINK} on the total amount of times that an investment can be made on link l. Certain modal links are also eligible for upgrades in order to allow for the usage of new fuels. Constraint (7.7) ensures that flow with a fuel that requires an upgrade in infrastructure on a modal link is only possible if an investment in that type of upgrade has been made in an earlier time period. Investments in infrastructure can also be made on arc level. These types of investments are related to filling and charging stations for specific fuels. The arc capacity restricts the flow on the arc in both direction to the base capacity. Linear expansion of this capacity is possible, which is shown in the charging and filling infrastructure constraint (7.8).

$$\sum_{p \in \mathcal{P}_s} \Big(\sum_{k \in \mathcal{K}_{im}^{o}} h_{kpt\xi} + \sum_{k \in \mathcal{K}_{im}^{d}} h_{kpt\xi} + \sum_{k \in \mathcal{K}_{im}^{Tr}} h_{kpt\xi} \Big) \leq Y_{ims}^{BASE,n} + Y_{ims}^{NODE} \sum_{\tau < t} z_{ims\tau\xi}^{node},$$
$$s \in \mathcal{S}_m, (i,m) \in \mathcal{NM}^{CAP}, t \in \mathcal{T}, \xi \in \Xi \tag{7.9}$$

$$\sum_{t \in \mathcal{T}} z_{imst\xi}^{node} \leq MAX_{ims}^{NODE}, \qquad s \in \mathcal{S}_m, (i,m) \in \mathcal{NM}^{CAP}, \xi \in \Xi \tag{7.10}$$

There are three types of flow that use available capacity in terminals: path flow for paths originating in the terminal, ending in the terminal or transferring modes at the terminal. Constraint (7.9) states that the total flow of goods being processed at a capacitated terminal i of type s with mode m can not exceed its capacity $Y_{ims}^{BASE,n}$. Additional capacity can be added through step-wise investments in the terminal, which is limited to a certain amount of steps as described by constraint (7.10).

$$\sum_{p\in\mathcal{P}}\sum_{a\in\mathcal{A}} E_{apt}x_{apt\xi} \leq CO2_t^{CAP} + v_{t\xi}, \qquad t\in\mathcal{T},\xi\in\Xi \tag{7.11}$$

The total greenhouse gas emissions of the system in each time period t is limited by the soft constraint (7.11), where $CO2_t^{CAP}$ the maximum quota in tonnes CO_2 set by the emission reduction limit. In order to ensure feasibility, this limit can be violated by the variable $v_{t\xi}$. A violation will trigger a penalty cost, as shown in the objective function.

$$\sum_{p\in\mathcal{P}}\sum_{a\in\mathcal{A}_{mf}} x_{apt\xi} \leq Y_{mft\xi}^{TECH}, \qquad (m,f)\in\mathcal{MF}^{NEW},t\in\mathcal{T},\xi\in\Xi \tag{7.12}$$

The maturity of new fuels f on a mode m in a time period t restricts the total usage in tonnes. This limit is referred to as $Y_{mft\xi}^{TECH}$, and is imposed by constraint (7.12). This parameter is indexed by ξ, as it contains uncertain data and varies by scenario.

$$x_{apt\xi} - x_{aptn} = 0, \qquad a\in\mathcal{A},p\in\mathcal{P},\xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.13}$$

$$h_{kpt\xi} - h_{kptn} = 0, \qquad k\in\mathcal{K},p\in\mathcal{P},\xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.14}$$

$$z_{lt\xi}^{link} - z_{ltn}^{link} = 0, \qquad l\in\mathcal{L}^{CAP},\xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.15}$$

$$z_{imst\xi}^{node} - z_{imstn}^{node} = 0, \qquad s\in\mathcal{S}_m,(i,m)\in\mathcal{NM}^{CAP},\xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.16}$$

$$z_{lu\xi}^{upg} - z_{lutn}^{upg} = 0, \qquad u\in\mathcal{U}_l^{LINK},l\in\mathcal{L}^{UPG},\xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.17}$$

$$v_{t\xi} - v_{tn} = 0, \qquad \xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.18}$$

$$y_{at\xi}^{charge} - y_{atn}^{charge} = 0, \qquad a\in\mathcal{A}^{Ch},\xi\in\mathcal{B}_n,n\in\mathcal{N}_t^{ST},t\in\mathcal{T}^{NL} \tag{7.19}$$

The non-anticipativity constraints for the variables are formulated in the same way as described in Section 7.1.4, and are given by constraints (7.13) - (7.19). This formulation is also valid for a multi-stage case.

$$x_{apt\xi} \geq 0, \qquad a\in\mathcal{A},p\in\mathcal{P},t\in\mathcal{T},\xi\in\Xi \tag{7.20}$$

$$h_{kpt\xi} \geq 0, \qquad k\in\mathcal{K},p\in\mathcal{P},t\in\mathcal{T},\xi\in\Xi \tag{7.21}$$

$$v_{t\xi} \geq 0, \qquad t\in\mathcal{T},\xi\in\Xi \tag{7.22}$$

$$y_{at\xi}^{charge} \geq 0, \qquad a\in\mathcal{A}^{Ch},t\in\mathcal{T},\xi\in\Xi \tag{7.23}$$

$$z_{imst\xi}^{node} \in \{0,1\}, \qquad s\in\mathcal{S}_m,(i,m)\in\mathcal{NM}^{CAP},t\in\mathcal{T},\xi\in\Xi \tag{7.24}$$

$$z_{lut\xi}^{upg} \in \{0,1\}, \qquad u\in\mathcal{U}_l^{LINK},l\in\mathcal{L}^{UPG},t\in\mathcal{T},\xi\in\Xi \tag{7.25}$$

$$z^{link}_{lt\xi} \in \{0,1\}, \qquad l \in \mathcal{L}^{CAP}, t \in \mathcal{T}, \xi \in \Xi \qquad (7.26)$$

The domain restrictions of the variables are given by constraints (7.20)-(7.26).

7.6.1 Strengthening the Big-M Formulation

Constraint (7.7) contains a big-M formulation through the parameter M_l. The use of big-M in a MIP may affect the performance of the model formulation negatively if it is set too high or too low. In the case of a too high big-M, a solver may interpret the binary variable z^{UPG}_{luts} as 0 if it is small enough to satisfy the integrality tolerance. This can happen while still allowing x_{apts} variables to have non-zero solutions without incurring the expensive fixed charge on z^{UPG}_{luts}. On the other hand, a too low value of big-M can result in feasible solutions being cut off.

In this model formulation big-M is chosen based on the modal link capacity constraint (7.5). From this constraint it is clear that the total flow of transportation on a link can never be more than the base capacity plus the total potential added capacity. Hence, the flow of all products on an arc which contains a fuel that require a link-based upgrade in infrastructure, such as contact line on a non-electrified railway, can at most equal this capacity. This is a valid statement as the links eligible for upgrade are a subset of the capacitated links. Big-M is for that reason chosen as the total possible capacity for each link that is suitable for upgrade. A lower value may cut off feasible solutions in the case of when only a single fuel is used for transportation on a link. The tightened big-M formulation is given in (7.27).

$$M_l = Y^{BASE,l}_l + Y^{LINK}_l MAX^{LINK}_l \qquad (7.27)$$

7.7 Path Generation

A central idea in a path formulation is to only use a subset of all possible paths to reduce computational complexity. In this section, we present the overarching steps and concepts behind our multi-mode path generation algorithm. Its main steps entail choosing the most promising transfer nodes, creating paths with a combination of all modes to and from the transfer nodes, and filtering out those paths which are never used various instances of our model.

In our model formulation, paths are defined as a set of directed modal links leading from an origin node to a destination node. Unlike standard modal links which are undirected, the modal links used in path generation have to be directed. This is because we need to know which is the origin node and which is the destination node in order for constraint (7.3) to work as intended.

7.7.1 Single-Mode Path Generation

For uni-modal transport, the procedure for generating paths is relatively straightforward. We first generate single link paths between all neighboring nodes that are directly connected in the road and rail networks. These links reflect the real-life roads and rail tracks.

Using these links we can generate the set of shortest paths between all nodes present in the road and rail networks through a breadth first search. Modelling road and rail paths this way is done in order to capture the capacity used on links, as this capacity is often constrained. Since transport between different nodes requires the utilization of the same railway tracks, railway paths must be defined by all links they use for the journey. This requires the ability to constrain yearly flow on all railway links to a certain threshold. The same goes for utilizing sustainable fuel options on road links, where constraints in the form of sufficient filling infrastructure occurs. For transport by sea, there are no capacity constraints on links. Consequently, all single-mode paths for sea can be modelled as direct links from source to destination.

7.7.2 Multi-Mode Path Generation

As for generating cost-effective multi-mode paths, a more sophisticated heuristic is required. There is no simple measure that can accurately capture which paths make up the most efficient transport routes. If we were to solely use distance with a given mode to determine shortest multi-mode paths, sea would rarely be chosen as journeys by sea are often lengthy, although cheap. If we instead only rely on some average cost of using a mode to find the optimal multi-mode paths, modes that might provide cost-effective and sustainable fuels in the future could be excluded. Thus, it becomes a challenge to generate suitable multi-modal paths beforehand. Instead we generate paths for all combinations of all possible modes between the origin node, the destination node, and a transfer node in between them. Afterwards, we filter out the the paths frequently used by various instances of our model. An overview of our path generation procedure is given by Algorithm 2.

Algorithm 2 Path generation algorithm

```
 1: procedure PathGeneration(ODpairs, DistanceMatrix)
 2:     PathsGenerated ← All generated paths
 3:     k ← number of nodes chosen for transfer between OD pair
 4:     cutoffLength ← some multiple of shortest OD path distance
 5:     for each OD pair do
 6:         Calculate k best transfer nodes from shortest intermediate distance
 7:         TransferNodes ← List of best transfer nodes for OD pair
 8:         for each TransferNode do
 9:             ModesOT ← All available modes between origin and transfer
10:             ModesTD ← All available modes between transfer and destination
11:             for each ModeOT and ModeTD do
12:                 if ModeOT != ModeTD then
13:                     Generate path with modeOT and modeTD
14:                     if length(path) ≤ cutoffLength then
15:                         Add path to PathsGenerated
16:     Run various test instances of the model
17:     Save frequently used paths
```

The first stage of Algorithm 2, from step 1 to step 7, determines where the mode transfers should occur. In step 2 to 4 some necessary variables are initialized. These include the (for now empty) list of paths called *PathsGenerated*. Two user specified parameters are set, namely k, the desired number of possible transfer nodes for each OD pair and $cutoffLength$, a parameter indicating the maximal distance a newly generated path can be. In step 5 to 7 of Algorithm 2, the procedure for finding the optimal transfer nodes between each OD pair begins. As there is no way to know beforehand which modes will be used in paths, we cannot use mode specific distances to determine shortest paths. Therefore, we employ Euclidean distance to find the most promising transfer nodes between each OD pair. For each OD pair a k shortest paths search is performed to retrieve the n most promising transfer nodes. The k shortest paths algorithm is an extension of Dijkstra's algorithm. Dijkstra's algorithm finds the shortest path from any two nodes in a weighted, non-negative graph. It works by iteratively searching through the unvisited nodes which are the lowest total distance from its source until it finds its target and the distance of all other possible paths exceed the optimal path. The k shortest paths algorithm works similarly, but continues the procedure until the k unique shortest paths are determined [Yen, 1970]. In order to avoid complexity, only one-transfer paths are accepted as promising paths. This is deemed a reasonable assumption since the vast majority of generated shortest paths contain a single transfer node. Single transfer transport is also most often chosen in reality as multiple transfers is expensive.

In the second stage of Algorithm 2, from step 8 to 15, we generate all possible mode-based paths with the transfer nodes provided by stage 1. For each transfer node, available mode options from the origin node to the transfer node are determined in step 9, as well as from the transfer node to the destination node in step 10. Then paths are generated with all possible mode combinations in steps 11 through 13. For instance, if road and rail are the only viable options, both to and from the transfer nodes, a total of two paths are generated, namely (road, rail) and (rail, road). In step 14, we compare the total length of the newly generated path to the shortest recorded path between the same origin and destination. If the new path is longer than a multiple of the shortest recorded path, the path is discarded. If not, the newly generated path is added to $PathsGenerated$.

The third and final stage in Algorithm 2 is to filter out unnecessary paths and thus reduce computational complexity. In step 16, we run various test instances of our model, and record which paths are used. The parameter variation in these test instances should reflect the parameter variation done when analyzing results, so that the recorded paths are the most relevant. This filtering can be effective since the multi-mode paths used remain mostly the same, no matter the instance. Additionally, only a small subset of multi-mode paths are actually used for transport. Finally, in step 17 we save only the paths that are commonly used as input for the final model.

Chapter 8

Case Study

In this chapter we present the network and data used for the application of our model to the Norwegian freight transportation system. First, we describe the network and paths generated in Sections 8.1 and 8.2, followed by a section on demand in 8.3. Section 8.4 outlines the fuels included in our case study. Then we provide an overview of all costs related to transportation in Section 8.5 and transfer costs in Section 8.6. Information in connection to capacity expansion investments for rail, sea and road is presented in Section 8.7, followed by data on emission factors and limits in Section 8.8. Finally, we present relevant data regarding carbon prices and maturities of new fuels in Sections 8.9 and 8.10 respectively. All costs are discounted to their net present value (NPV) based on a 2 % risk-free interest rate.

8.1 Nodes, Arcs and Modal Links

In our case study we wish to encompass the entire freight transportation system in Norway, including import and export. To achieve this, we use the Norwegian counties as nodes, where Oslo and Viken are counted as one because of their close proximity. Additionally, we have nodes for the continental shelf, North and South Sweden, Europe and the remaining world. Each region is represented by a city, normally the largest city in the county or region, and distances between regions are calculated using the corresponding cities. These cities are also normally the site of the largest harbours and terminals in their county or region. For the continental shelf, the Johan Sverdrup platform is used as the geographical center, Hamburg is used for Europe, and the average distance to New York and Hong Kong is used for the world. While the city is used to calculate the distance between regions, the demand we use is the demand for the entire region. The regions we use for Norway and Sweden, as well as the continental shelf, are shown in Figure 8.1. Here, the main city is also indicated. For transport to and from Europe and the world, the calculated distance is cut in half in order to reflect the way transport costs and emissions should be distributed equally between the countries.

Nodes are connected by arcs, which are defined by the mode and fuel combination used as well as the nodes it connects. These arcs correspond to a modal link which represents the physical infrastructure present between the two nodes for a certain mode. Not all pairs of nodes have a modal link, and thus arc flow, with each mode between them. Sea paths are modelled as direct links between all nodes, except for Innlandet county which does not have a coast line. The continental shelf and the world can only be reached by sea transport. For road and rail we include modal links, and consequently corresponding arcs, between nodes that are directly connected through the existing infrastructure for the modes. For rail, we use all railway lines and for road we use the main roads that are used for freight transport. This means that sea transport between, for instance, Oslo and Trondheim can be modelled as a path with a single modal link, while for road and sea this is modelled as a path with multiple modal links, in this case between Oslo and Hamar and then Hamar and Trondheim. This way of modelling the road and rail transport allows us to limit the capacity in the networks. A complete overview of the possible modal links between each node is presented in Table 3 in Appendix B.

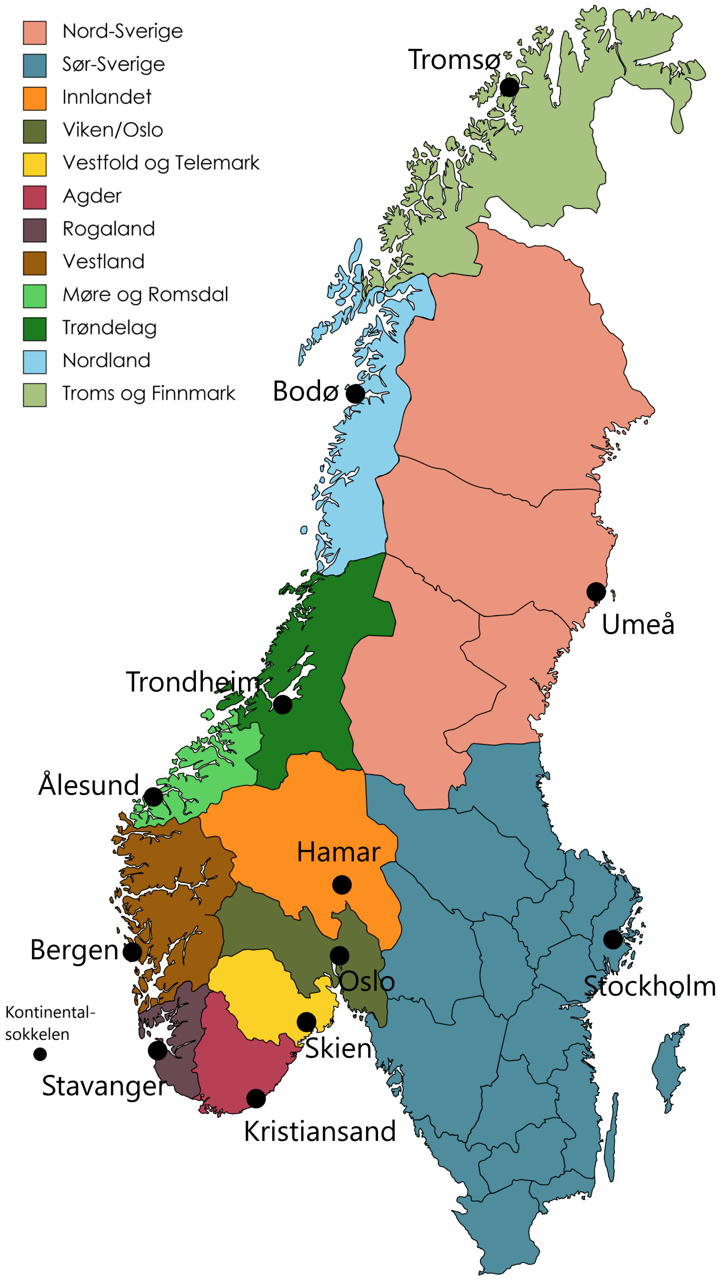


Figure 8.1: The counties in Norway, regions of Sweden and the continental shelf, which are used as nodes in our network. The main city is marked.

8.2 Generated Paths

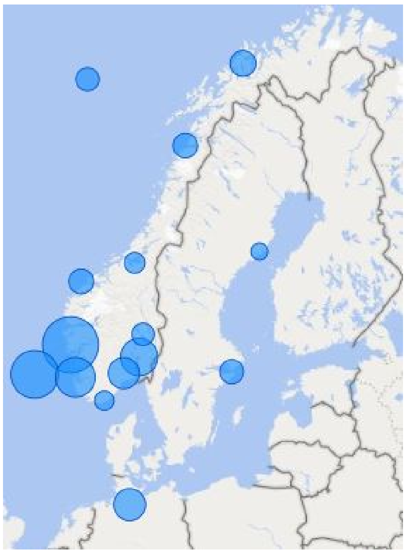
All nodes are connected to the road and railway network, except the continental shelf and the world (beyond Europe). All nodes, except Innlandet which has no coastline, are reachable by sea. This results in 550 uni-modal paths when running our uni-modal path generating algorithm. When generating the multi-modal paths with Algorithm 2, the number of transfer nodes k is set to three per OD pair. This parameter is set through running some test instances and evaluating the generated paths. For our network of nodes, three possible transfer nodes appears to provide sufficiently logical and varied paths. The maximum length of a newly generated path is set to three times the shortest available single-mode path between the OD pair. This parameter is set from trial and error, and appears to capture sensible paths, while discarding unnecessary long paths between neighbouring nodes. With these parameter settings, over 2000 unique multi-mode paths are initially generated by Algorithm 2 before the filtering stage. After running some test instances of our model, we observe that only about 250 of these multi-mode paths are ever used. Our final filtering procedure only saves the multi-mode paths that are used at any time period in any scenario of our base case. After filtering, we reduce the number of multi-mode paths down to 206. This gives us 756 paths in total. The filtering stage cuts the time constructing each scenario to a third. This is central, as initializing each scenario of an instance is the most time consuming part of solving the model. Filtering also reduces the time it takes to solve the model due to the reduced solution space.

8.3 Demand

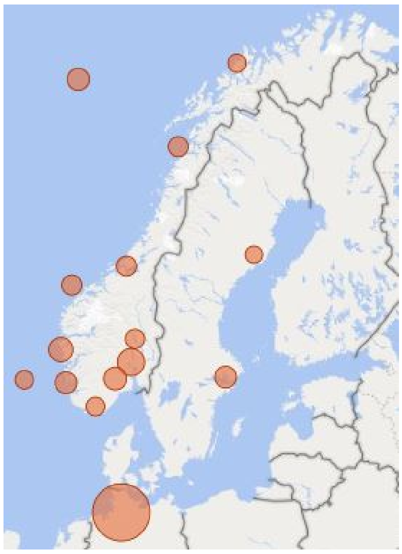
The demand between regions is provided by estimates from NGM. This includes demand forecasts for future time periods, which is presented in Table 8.1. Demand is defined as the amount in tonnes of a product that is to be transported annually from one region to another. NGM is detailed with every Norwegian municipality and many international cities represented as nodes. Therefore, the demand of municipalities within the same county as our selected regions is aggregated in order to reflect the demand of the whole county. As we focus on long-haul transportation, we remove all demand in which the origin and destination is the same region. We are then left with around 55 % of total demand, which is visualised in Figure 8.2.

Table 8.1: Demand in each time period given in million tonnes.

	2022	**2025**	**2030**	**2040**	**2050**
Demand	240.9	256.3	275.3	272.2	294.7



(a) Demand of goods from all nodes.



(b) Demand of goods to all nodes.

Figure 8.2: The demand of goods for 2022 from and to all nodes in our network. A larger bubble represents a larger demand. The world node is located up to the left.

8.4 Fuels

We distinguish between established mode-fuel combinations and new mode-fuel combinations. We classify mode-fuel combinations as established if they possess all of the following characteristics: they already exist in today's freight transportation fleet, they do not have a technological maturity limit, and they have already reached most, if not all, of their cost reduction potential. An overview of the two categories is given in Table 8.2. The table also distinguishes between the zero-emission fuels, which are battery electricity, hydrogen and ammonia, and the climate neutral fuels, which are biodiesel and biogas.

As mentioned, there also exists hybrid trains that can run on both diesel and electricity through CL-technology. This technology is not explicitly included, because these trains will be modelled as diesel trains when used on non-electrified lines and as electric CL trains on electrified lines. This will ensure the right emission factors and costs when used on the different kind of infrastructure.

Table 8.2: Overview of established and new mode-fuel combinations. The fuels marked in green are sustainable, where the dark green are zero-emission and the light green have emissions in a tank-to-wheel perspective.

Mode	Established fuels	New fuels
Road	Diesel	Battery
		Hydrogen
		Biodiesel
		Biogas
Sea	HFO	Hydrogen
	MGO	Ammonia
	LNG	Biodiesel
		Biogas
Rail	Diesel	Battery
	Electricity (CL)	Hydrogen
		Biodiesel

8.5 Generalized Transportation Costs

The generalized transportation cost estimates are based on an ongoing research project on the development of sustainable fuel costs within the FME MoZEES project [Martin et al., 2021]. This project provided us with costs for diesel and hydrogen for road, as well as HFO, hydrogen and ammonia for sea. The costs are levelized costs from well-to-wheel and are based on an average case where the electricity used in production comes from onshore wind power. Both capital and operational expenditures are considered, which means that fuel costs, wages, maintenance, cost of the vehicle and a weighted average cost of capital of 6 % are included. The costs do not include any taxes or subsidies, or any costs related to energy station infrastructure.

The numbers were given as €/km, so to arrive at a cost in NOK/tkm an exchange rate of 9.63 NOK/€ was used as it was the exchange rate on the 30th of March 2022 [Norges Bank, 2022]. To get the cost per tkm, the cost per km was divided by the capacity of the different vehicles, arriving at different costs per product groups. The capacities of the various vehicles are from Grønland [2018], and are listed in Table 2.

To get the cost for the remaining fuels for road, Pinchasik et al. [2021] was used to get relative cost estimates and development compared to diesel. For sea, Cepeda et al. [2019] was used to get the relative costs of HFO, MGO and LNG, and Ryste [2019] and Maas [2020] was used to get the relative costs of sustainable fuels. We were not provided generalized transport cost for rail. Costs for electric rail was found in Meulen et al. [2020] for the various train types, hence capacity for various train types was not needed. Relative costs for the other fuels were found in Jernbanedirektoratet [2019b] and Zenith et al. [2019].

The full cost numbers are given in Appendix C, while an excerpt is displayed in Table 8.3. The numbers marked in blue are from Martin et al. [2021], while the rest are estimates based on relative costs. For ammonia and hydrogen the costs are 9999 for 2022 and 2025, which means they are unavailable in these years. The numbers presented here are used as average costs in further analysis. We also test instances with higher and lower cost, where the average costs for all new fuels are increased or decreased by 25 %. This is based on best and worst case estimates provided by Martin et al. [2021].

Table 8.3: The generalized transportation costs of dry bulk for all modes, fuels and years.

Mode	Product group	Fuel	2022	2025	2030	2040	2050
Road	Dry bulk	Diesel	0.6589	0.6584	0.6584	0.6584	0.6579
Road	Dry bulk	Battery electric	0.8566	0.6782	0.5991	0.5596	0.5460
Road	Dry bulk	Hydrogen	1.0731	0.9367	0.8338	0.7395	0.7085
Road	Dry bulk	Biodiesel	0.6985	0.7308	0.7440	0.7572	0.7697
Road	Dry bulk	Biogas	0.7380	0.7440	0.7374	0.7308	0.7237
Sea	Dry bulk	HFO	0.0749	0.0748	0.0748	0.0747	0.0747
Sea	Dry bulk	MGO	0.0824	0.0823	0.0823	0.0822	0.0821
Sea	Dry bulk	LNG	0.0882	0.0881	0.0880	0.0879	0.0879
Sea	Dry bulk	Hydrogen	9999	9999	0.1625	0.1316	0.1080
Sea	Dry bulk	Ammonia	9999	9999	0.1571	0.1302	0.1053
Sea	Dry bulk	Biodiesel	0.0989	0.1004	0.1020	0.1036	0.1051
Sea	Dry bulk	Biogas	0.1038	0.1055	0.1071	0.1087	0.1104
Rail	Dry bulk	Diesel	0.1387	0.1387	0.1387	0.1387	0.1387
Rail	Dry bulk	Electric train	0.1156	0.1156	0.1156	0.1156	0.1156
Rail	Dry bulk	Hybrid	0.1525	0.1525	0.1525	0.1525	0.1525
Rail	Dry bulk	Battery train	0.1664	0.1636	0.1609	0.1567	0.1525
Rail	Dry bulk	Hydrogen	0.2773	0.2496	0.2219	0.1941	0.1733
Rail	Dry bulk	Biodiesel	0.1456	0.1470	0.1484	0.1498	0.1512

8.6 Transfer Costs

When transferring goods from one mode to another, costs related to loading and unloading occurs. Loading/unloading costs are calculated based on the directs costs related to staffing and equipment, and the time costs of the vehicle during the loading/unloading. Transfer between certain vehicle types can be done directly without stuffing or stripping the goods from the containers or other transport units. This includes transfer between the vehicles combi train, articulated semi truck (closed and with containers) and container ship. The costs for these types of transfers are for that reason calculated as the total loading/unloading costs between the modes minus the costs related to stuffing/stripping.

The transfer costs between the different modes are based on calculations done by Grønland [2018], and are presented in Table 8.4. We only consider costs related to the type of vehicle the product can be transported by within a mode. Additional product dependent costs, such as product fees in the harbours, time costs during transportation and storage costs are not taken into consideration in this case study. The costs per shipment unit is also neglected by advise from TØI, as the costs per tonne constitutes the majority of the total transfer costs.

Table 8.4: The cost of transferring the various product groups from one mode to another. The numbers are given in NOK and are from Grønland [2018].

From	**To**	**Dry bulk**	**Wet bulk**	**Fish**	**General cargo**	**Industrial**	**Thermo**	**Timber**
Sea	Rail	106	66	66	293	66	133.5	111
Sea	Road	108	356	26	254	356	112	116
Rail	Road	4	381	57	57	381	35.5	17

8.7 Capacities and Investments

In this section we detail the current capacities and options for capacity expansions for modal links, nodes and arcs. We first present investments for rail where capacity expansions in both rail links and rail terminals are possible, as well as partial or full electrification of non-electrified lines. Then, we provide similar data for capacity expansions in sea harbours. Finally, we present the figures behind the option to invest in charging infrastructure for new fuels on road. All investments for sea and rail have to occur in the time period before the added capacity or partial or full electrification can be put to use.

8.7.1 Rail Infrastructure

Rail is restricted both by the capacities on the railway lines, as well as the capacities in railway terminals. The capacity on most railway lines was found in Jernbanedirektoratet [2020], and the remaining capacities were estimated from Jernbaneverket [2011], Svingheim [2021a] and Jernbaneverket [2006b]. All capacities are presented in Table 8.5. Nord-Norgebanen from Bodø to Tromsø does not exist, but is added as a possible investment in our model. It is therefore included as having no capacity yet.

Table 8.5: The current capacity on Norwegian railway lines and possible capacity increasing investments with associated costs.

From	To	Capacity (tonnes)	Capacity increase (tonnes)	Costs (MNOK)
Oslo/Viken	Vestfold og Telemark	1 250 000	150 000	227
Vestfold og Telemark	Agder	1 250 000	150 000	227
Agder	Rogaland	1 250 000	150 000	227
Oslo/Viken	Vestland	1 500 000	750 000	289
Oslo/Viken	Innlandet	1 600 000	650 000	275
Innlandet	Møre og Romsdal	250 000	250 000	100
Innlandet	Trøndelag	1 600 000	650 000	275
Innlandet	Trøndelag	250 000	250 000	100
Trøndelag	Nordland	650 000	450 000	430
Nordland	Troms og Finnmark	0	650 000	113 000
Oslo/Viken	Sør-Sverige	1 000 000	300 000	500
Innlandet	Sør-Sverige	800 000	300 000	927
Trøndelag	Nord-Sverige	250 000	250 000	100
Nordland	Nord-Sverige	800 000	300 000	927

The capacity on railway lines can be increased through a one-time investment. The additional capacity and cost of this investment can be seen in Table 8.5. These numbers are based on Jernbanedirektoratet [2020]. The numbers for Raumabanen, Meråkerbanen and Rørosbanen are estimated based on the other numbers, as these are not given. Here a doubling of capacity is assumed. The cost of Nord-Norgebanen is the total investment cost for building a new and fully electric railway line between Bodø and Tromsø [Jernbanedirektoratet, 2021c]. The capacity for this railway line is set to the same as today's capacity on Nordlandsbanen, as these are similar lines in terms of climate and landscape. Nord-Norgebanen is also likely to be built as a single tracked line, equivalent to Nordlandsbanen today [Bentzrød, 2021].

The capacities for rail terminals are aggregated over the counties. The capacities for combi terminals are from Jernbanedirektoratet et al. [2020] and Grønland & Hovi [2014]. The timber terminal capacities are from Bårdstu [2014], Pedersen [2020], Pettersen & Ruud [2022] and Gurandsrud [2015]. The capacity of small timber terminals is estimated from numbers from similarly small terminals. A conversion factor of 0.7 is used from m^3 to tonnes, based on Larvik havn [2021]. We assume that there are no capacity limitations on foreign railway terminals.

Table 8.6: The capacity of Norwegian railway terminals.

County	**Capacity combi (tonnes)**	**Capacity timber (tonnes)**
Oslo/Viken	6 365 000	380 000
Agder	475 000	0
Rogaland	1 425 000	0
Vestland	1 378 000	0
Møre og Romsdal	285 000	0
Trøndelag	1 330 000	0
Nordland	1 780 300	0
Innlandet	0	1 785 000
Vestfold og Telemark	0	56 000
Troms og Finnmark	0	0

For capacity increasing investments in railway terminals, the costs and associated increase in capacity is determined by the terminal's original size. The combi terminals are divided into three size groups, where the first consists of only Oslo/Viken and can increase the terminal capacity by 700 000 tonnes each time period with the cost of 737.1 MNOK. The second group consists of the medium sized terminals in Rogaland, Vestland, Trøndelag and Nordland. These terminals can increase their capacity by 500 000 each period with the associated cost of 526.5 MNOK. Finally, the third group of small and non-existent terminals consists of Agder, Møre og Romsdal, Innlandet, Vestfold og Telemark and Troms og Finnmark. This group can increase their terminal capacity by 200 000 tonnes in each time period with the cost of 210.6 MNOK. The costs are based on the cost of the capacity increasing investments planned for the Alnabru terminal in Oslo [Jernbanedirektoratet, 2019d]. For the timber terminals, Oslo/Viken can increase capacity by 200 000 tonnes for 120 MNOK, Innlandet can increase it by 500 000 tonnes for 300 MNOK and Vestfold og Telemark can increase it by 50 000 tonnes for 30 MNOK. These capacity increases are determined by the original size of the timber terminal and can be added each time period. The costs are based on Pettersen & Ruud [2022]. Timber terminals cannot be opened in counties that do not already have a timber terminal. A capacity increasing investment for a railway terminal, both combi and timber, can be performed once each time period up to and including 2040.

Other than capacity increasing investments on railway lines, it is also possible to invest in partial or full electrification on a line. A non-electrified line can run diesel, biodiesel and hydrogen, while a partially electrified line also can run battery trains and a fully electrified line can run all rail fuels. The costs of partial and full electrification are found in Jernbaneverket [2015], Bane Nor [2021b] and Svingheim [2019], and listed in Table 8.7.

Table 8.7: The cost of partially of fully electrifying non-electrified railway lines.

Railway line	**Fully electrified (MNOK)**	**Partially electrified (MNOK)**
Nordlandsbanen	14 000	3 300
Rørosbanen and Solørbanen	8 100	1 875
Raumabanen	2 200	500

8.7.2 Sea Infrastructure

Sea transport is restricted by the capacity in harbours. The maximum capacity is found by using statistics over the number of tonnes transported to and from all Norwegian harbours in 2020 [Statistisk sentralbyrå, 2020a], which is then summed up over all harbours in a county. The maximum capacity is assumed to be the total amount of tonnes transported plus an additional 50 %, which is shown in Table 8.8. This is based on Caspersen & Hovi [2014] showing that the harbours in Oslofjorden have available capacity of between 28 % and 82 %, and correspondence with Moss harbour who said they are currently using 2/3 of their capacity. All Norwegian counties have harbours, except for Innlandet which has no coastline. Foreign harbours are assumed to have no restriction in capacity.

Capacity increasing investments in harbours are possible to do once each time period up to and including 2040. The number of tonnes a county can increase its harbour capacity by in each time period is calculated as 30 % of the original capacity. The cost is based on the investment cost in NOK per tonnes from the extension of Karmsund harbour in Rogaland [Jørgensen, 2020].

Table 8.8: The capacity of Norwegian harbours and possible capacity increasing investments.

County	**Capacity (tonnes)**	**Capacity increase (tonnes)**	**Cost (MNOK)**
Oslo/Viken	19 498 000	5 849 000	523
Agder	9 708 000	2 912 400	260
Rogaland	22 902 000	6 870 000	614
Vestland	100 114 000	30 034 000	2 685
Møre og Romsdal	18 310 000	5 493 000	491
Trøndelag	7 806 000	2 342 000	209
Nordland	52 811 000	15 843 000	1 417
Vestfold og Telemark	38 407 000	11 522 000	1 030
Troms og Finnmark	9 510 000	2 853 00	255
Innlandet	0	0	0

8.7.3 Energy Station Infrastructure

The costs and capacity for charging and filling infrastructure for road transport are found Thema Consulting Group [2022]. Here, numbers related to the maximum distance between stations are given, which are used to calculate the number of stations needed for an arc, and the related cost for this infrastructure. This cost is then divided by the annual capacity in tonnes these stations provide. The resulting cost estimates are presented in Table 8.9. The base charging and filling capacity for road is assumed to be zero, as there is a limited amount of existing infrastructure and its capacities are mostly unknown.

Table 8.9: The cost of investing in charging and filling stations for road. The numbers are noted in NOK/tonnes.

Fuel	**Cost of energy station (NOK/tonnes)**
Battery electric	0.2283
Hydrogen	0.0676
Biogas	0.0338

Charging and filling infrastructure for sea and rail transport is not included in this case study. These investment costs are assumed to be lower since filling infrastructure will most likely only be necessary in the origin and destination terminals, and not along the journey as with road. Secondly, the cost of these investments is highly uncertain. For sea, the cost of a hydrogen filling station is dependent on many factors, such as the type of ship in question and whether the hydrogen is compressed or in liquid form. For ammonia, direct bunkering is considered, which would eliminate the need for on-shore filling stations [DNV, 2021]. For rail, the hydrogen stations are assumed to be located where diesel stations are located today. The costs of these stations is assumed to not be much higher compared to a conventional diesel filling station for the companies that utilize hydrogen, as the construction costs are subject to commercial depreciation rates (E. Fure, personal communication, May 20, 2022).

8.8 Emission Data

In this case study, we consider the GHG emissions of fuels in a well-to-wheel perspective. All emissions are provided as gCO_2/tkm, where CO_2 refers to CO_2 equivalents. Again, the emissions are divided by the capacity of the various vehicles, arriving at different emission factors for different product groups. We assume that electricity, hydrogen and ammonia have no emission in production, though this is dependent on the energy source and production method. In our case, these fuels will have zero emissions.

For road transport, Hagman [2019b] was used for emission factors for all fuels in 2022. The development in emissions until 2050 is estimated from Fedoryshyn & Thovsen [2018]. For sea and rail transport, emission factors for various diesel vessels and trains are provided by VVT [2017], a Finnish research centre. Jernbaneverket [2006a] was used for biodiesel on rail, and Cepeda et al. [2019] and Haugland et al. [2022] was used for remaining fuels on sea. A small selection of the emission factors used is shown in Table 8.10, while the entire table is presented in Appendix C.

Table 8.10: Emission factors for the various mode and fuel combination for dry bulk for all time periods in gCO_2/tkm.

Mode	**Product group**	**Fuel**	**2022**	**2025**	**2030**	**2040**	**2050**
Road	Dry bulk	Diesel	69.24	67.80	65.46	61.02	56.88
Road	Dry bulk	Battery electric	0	0	0	0	0
Road	Dry bulk	Hydrogen	0	0	0	0	0
Road	Dry bulk	Biodiesel	9.35	9.15	8.84	8.24	7.68
Road	Dry bulk	Biogas	8.48	8.30	8.01	7.47	6.96
Sea	Dry bulk	HFO	13.00	12.73	12.29	11.46	10.68
Sea	Dry bulk	MGO	12.09	11.59	10.80	9.39	8.16
Sea	Dry bulk	LNG	9.10	8.72	8.13	7.07	6.14
Sea	Dry bulk	Hydrogen	0	0	0	0	0
Sea	Dry bulk	Ammonia	0	0	0	0	0
Sea	Dry bulk	Biodiesel	11.70	11.22	10.46	9.09	7.89
Sea	Dry bulk	Biogas	3.12	2.99	2.79	2.42	2.11
Rail	Dry bulk	Diesel	18.80	18.41	17.77	16.57	15.44
Rail	Dry bulk	Electric train (CL)	0.00	0.00	0.00	0.00	0.00
Rail	Dry bulk	Hybrid	13.16	12.62	11.76	10.22	8.88
Rail	Dry bulk	Battery train	0	0	0	0	0
Rail	Dry bulk	Hydrogen	0	0	0	0	0
Rail	Dry bulk	Biodiesel	3.76	3.60	3.36	2.92	2.54

The total CO_2 emissions in each time period cannot exceed the emission limit of that time period, in accordance to Table 8.11. The percentages given in 2030 and 2050 reflect actual emission reduction goals determined by the Norwegian government, while the other values are extrapolated from these goals. We use total emissions in 2022 according to our model, as the base emission rate. This number is reduced by the percentage given in Table 8.11 until emissions are eliminated in 2050. In reality, the Norwegian government has planned to use 2005 emissions as base value. This does not pose a problem, however, as 2005 and 2022 emission levels are very similar [Miljødirektoratet, 2020a].

Table 8.11: Emission limit for each time period as a percentage of CO_2 emissions in 2020.

	2022	**2025**	**2030**	**2040**	**2050**
Emission limit	100 %	75 %	50 %	25 %	0 %

The emission violation penalty is set to 500 NOK/gCO_2, which is more than sufficiently high enough to enforce maximum compliance with the emission limit constraint. This is done in order to be able to see what the solution becomes when the best possible emission reduction for each scenario is enforced.

8.9 Carbon Prices

Today's carbon price is 766 NOK per tonne CO_2 [Regjeringen, 2021]. This price has been proposed by the Norwegian government to gradually increase towards 2000 NOK per tonne CO_2 in 2030. In the computational study we consider a further increase with the same growth rate until 2050 as part of the base case instance. We also consider a carbon price development with a price of 3000 NOK per tonne CO_2 in 2030 and further gradual growth until 2050 in other instances, to investigate how a stricter carbon price policy affects the results. The alternatives for carbon price development are presented in Table 8.12. These prices are multiplied with the emission factors and added to the transportation costs to obtain the total generalized transportation cost estimates for each mode-fuel combination.

Table 8.12: Carbon price development in NOK/tonne CO_2.

	2022	**2025**	**2030**	**2040**	**2050**
Base case	766	1272	2000	3456	4912
Higher price	766	1772	3000	5456	7912

8.10 Maturity Limits

To reflect that new fuel technologies might not be available today, and are likely to only be partially available in the future, we wish to limit the amount of new fuels that can be used. As mentioned, we define a mode-fuel combination's maturity as how much demand a mode and fuel combination can cover in a time period. The maturity limits are assumed to be known in the earliest time periods, 2022 and 2025, and becomes uncertain from 2030 up until 2050. Consequently, the latter time periods belong to the problem's second-stage. We present three main predictions for maturity development, low, medium and high for each fuel. The full overview over the maturity for all fuels in the different predictions, is found in Appendix E, while an excerpt is presented in Table 8.13. All conventional fuels have a 100 % maturity level.

Table 8.13: The maturity level development of hydrogen for the various modes in all scenarios.

Scenario	Mode	Fuel	2022	2025	2030	2040	2050
L	Road	Hydrogen	0 %	0 %	0 %	1 %	2 %
L	Sea	Hydrogen	0 %	0 %	0 %	0 %	0 %
L	Rail	Hydrogen	0 %	0 %	0 %	0 %	0 %
M	Road	Hydrogen	0 %	0 %	5 %	15 %	25 %
M	Sea	Hydrogen	0 %	0 %	2 %	6 %	10 %
M	Rail	Hydrogen	0 %	0 %	1 %	3 %	5 %
H	Road	Hydrogen	0 %	0 %	10 %	25 %	50 %
H	Sea	Hydrogen	0 %	0 %	5 %	12 %	30 %
H	Rail	Hydrogen	0 %	0 %	2 %	6 %	10 %

The maturity levels are stated as percentages, which refer to what proportion of the fleet of vehicles within the mode that can utilize a fuel in a time period. For instance, for road transport, 50 % of the transport in 2050 can be done by a hydrogen truck. In order to scale this to the percentage of total demand a mode and fuel combination can cover, we put a limit on how much a mode can cover of the total demand. The limits are 40 % for road, 75 % for sea and 5 % for rail. This is based on the distribution between modes presented in Table 2.1, though scaled to the distribution between domestic and international transport in our demand data. We added some slack to allow for a modal shift.

There are few numbers related to fuel technology maturity available. Our scenarios are based on numbers and discussions from Fridstrøm & Østli [2021] and Handberg et al. [2019] for road fuels, Handberg et al. [2019] and Miljødirektoratet [2020a] for sea fuels and Jernbanedirektoratet [2019c], Jernbanedirektoratet [2019b] and Bane Nor [2021b] for rail fuels.

When we construct scenarios for our stochastic model instance, we can combine the maturity levels in different ways. One way is to have all fuels high in one scenario, medium in another and low in the last scenario. However, it is unlikely that all fuel groups will have the same development and be invested in equally. Thus modelling all fuels to mature in the same manner might not yield very interesting results. Instead, we choose to separate the new fuels into three fuel groups in which all the fuels in the same group are assumed to co-vary. These three groups are fuels related to battery electricity, hydrogen related fuels and biofuels. A full overview over the fuel groups is shown in Table 8.14. Fuels within a fuel group have the same maturity level to reflect innovation for the fuel in general and possible synergy effects between the same fuel for different modes.

Table 8.14: An overview of the mode and fuel combinations that belong to each fuel group. Only new fuels are included as these are the ones with maturity limits.

Battery electricity	**Hydrogen**	**Biofuels**
Road - Battery electric	Road - Hydrogen	Road - Biodiesel
Rail - Battery train	Sea - Hydrogen	Road - Biogas
	Sea - Ammonia	Sea - Biodiesel
	Rail - Hydrogen	Sea - Biogas
		Rail - Biodiesel

When each of the three fuel groups can either have a high or a low maturity, this results with eight scenarios representing every combination. An example of a scenario is HLH, where the first letter signifies that each fuel in the battery electricity group has a maturity limit equal to their high maturity. The second letter refers to all fuels in the hydrogen groups having their low maturities respectively, and the third letter refers to all biofuels having their high maturities respectively.

Chapter 9

Computational Study

In this section we present the results of our computational study. First, in section 9.1 present our computational results. In sections 9.2 and 9.3 we present the results of our two main model instances respectively. For each instance we discuss the results in terms of objective value, emission reduction, mode-fuel mix and investment rate. We compare the stochastic solution to the deterministic version to gain insight into the effects of uncertainty. This includes calculating the Value of the Stochastic Solution. Finally, for each instance we perform sensitivity analysis on probabilities and costs in order to test the robustness of our optimal solution.

Note that when we compare scenarios which pertain to the same stochastic model, we mostly discuss decision variables from 2030 and beyond. This is because all decision variables before this stage are the same for all scenarios. On the other hand, when comparing different stochastic models to each other, we mainly focus on the decision variables for 2022 and 2025. This is because these constitute the first stage variables, which have to be decided before the uncertainty in maturity is realized.

All model instances are run on a Lenovo NextScale nx360 M5 with a 2x 2.3GHz Intel E5-2670v3 processor, 12 cores and 64Gb RAM. Gurobi 9.5 is used as solver and Python's Pyomo framework is used for model implementation. All source code is available in AIM [2022].

9.1 Solution Method and Computational Results

When solving large mixed-integer stochastic programs, progressive hedging (PH) can find the optimal solution, or a an acceptable feasible solution, in cases where solving the extensive formulation (EF) directly in a general-purpose solver is too time consuming. We test the two solution methods on our initial model instance, later referred to as the ambitious case. When comparing computation times for the two solution methods, detailed in Table 9.1, progressive hedging appears to take five times as long as solving the extensive formulation in its entirety. The optimality gap is also worse with progressive hedging after 132.3 seconds, compared to the optimality gap after 24.4 seconds with solving the extensive formulation directly. Gurobi actually solves the extensive formulation relatively fast, signalling that the relatively small size of our model does not require a more sophisticated solution method. The tractability of our model is in large part due to the path generation algorithm, which filters out unnecessary paths and reduces complexity. Additionally, as the optimality gap for progressive hedging is worse, we are left with little incentive to use progressive hedging for our case study. Thus we only solve the extensive formulation of the instances in the computational study from now on. As the model solves efficiently, we do not delve deeper into computational analysis of the model.

Table 9.1: A comparison of the performance of EF and PH.

Solution method	**Time (s)**	**Optimality gap**
EF	24.4	< 0.01 %
PH	132.3	0.048 %

9.2 Ambitious Case

In our initial case, from now on referred to all the ambitious case, the three fuel groups are either at low or high maturity development. This leads to eight scenarios for how the fuel groups can mature. Each scenario is given an equal probability in this case. Thus scenario HLH means battery electricity is at high maturity, hydrogen-based fuels are at low maturity and biofuels have high maturity again. Then the best case scenario for maturity development is given by scenario HHH, while the worst case scenario is given by LLL. We wish to reduce emissions gradually in accordance to Table 8.11. The resulting model has 340535 constraints 639481 variables, of which 1960 are binary variables.

Table 9.2: Objective value and computational time for the ambitious case.

Instance	**Objective value (BNOK)**	**Objective value excl. penalty (BNOK)**	**Time (s)**	**Optimality gap**
Ambitious case	154 783.55	287.74	24.4	< 0.01 %

As stated in Table 9.2, this instance solves to optimality in 24.4 seconds. The solution is penalized heavily since it fails to comply with the emission reduction constraints. Therefore the true total costs is much lower when the emission violation penalty is removed. For the entire system, we get a total net present value cost of 287.7 billion NOK when subtracting the penalty cost. The massive penalty cost of 500 NOK/gCO_2 not only affects the objective function value, but also the solution as is enforces maximum possible compliance with the emission limit constraint.

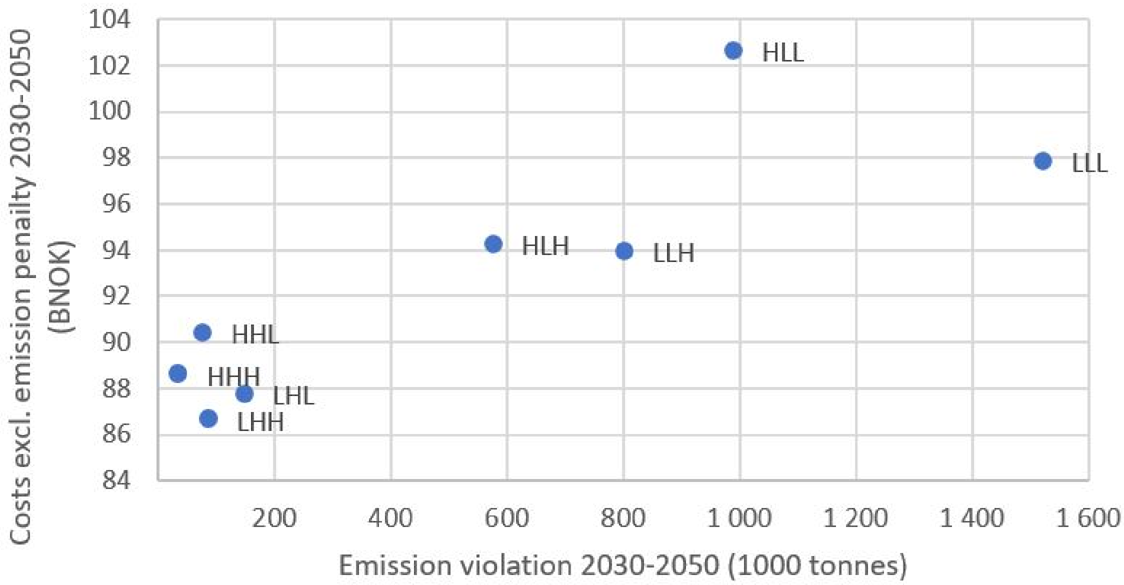


Figure 9.1: The emission violation and cost for 2030 to 2050 for all scenarios in the ambitious case.

From Figure 9.1 we can observe how the emission violation relates to the total costs for each scenario. The HHH scenario manages to reduce emissions the most, but even in this optimistic scenario, almost 38 000 tonnes of CO_2 emissions in 2050 is unavoidable. The cheapest scenario appears to be LHH where battery electric vehicles have a low maturity development, while hydrogen and biofuels have high. In this scenario, however, the emission violation is twice as large. A key takeaway from Figure 9.1 is that all scenarios where hydrogen-based fuels have high maturity are both relatively cheap and produce the lowest emissions by far. This signals that hydrogen and ammonia are essential for a sustainable energy transition in the transport sector. The scenario where only electricity based fuels have high maturity, HLL, is by far the most expensive and has a significant amount of emissions. This is likely because there are no electricity based fuels for sea transport. Goods will therefore have to be transported with other, more expensive, modes or with fuels with high emissions.

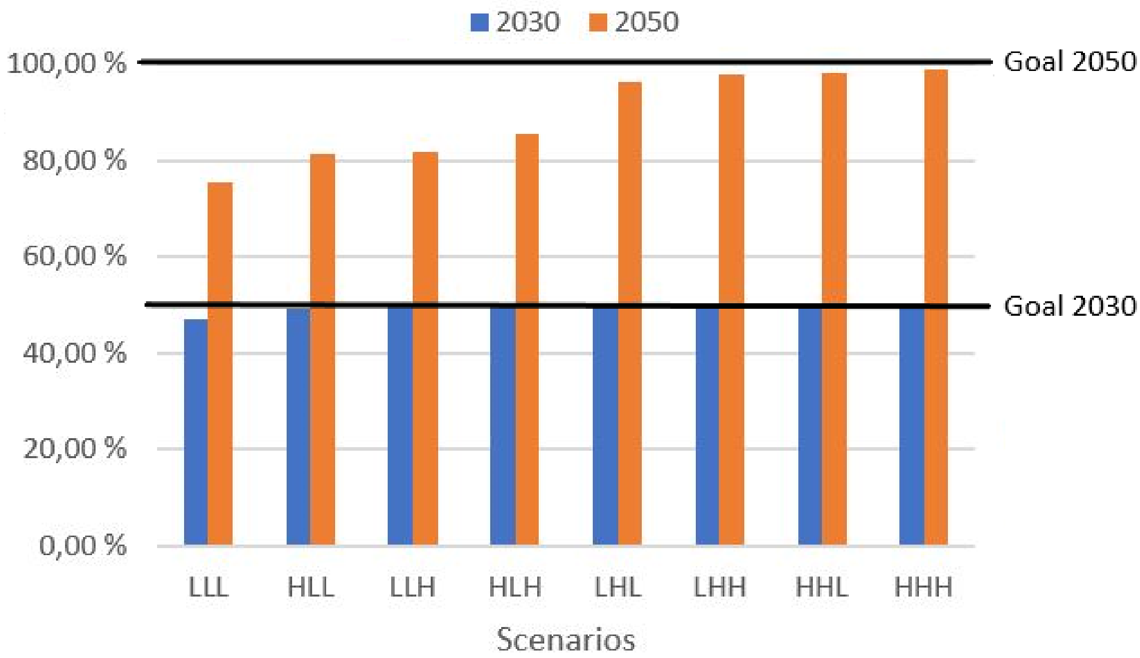
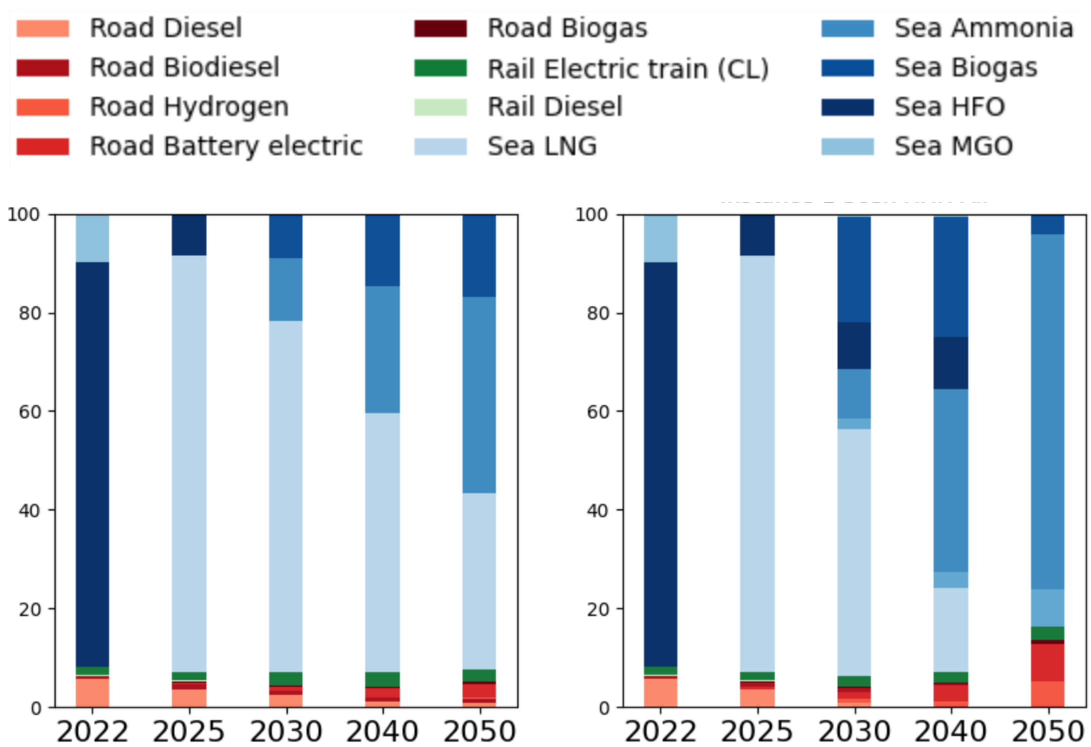


Figure 9.2: The emission reduction in each scenario in the ambitious case compared to the emission reduction goals. The reduction is given in percentage of the 2022 emission level.

Figure 9.2 provides a breakdown of how much emissions are reduced by in 2030 and 2050 for each scenario. We observe, as before, that in all scenarios where hydrogen-based fuels are of high maturity, the emission reduction goals of 50 % in 2030 is reached. Though cutting emissions entirely in 2050 is not feasible in any scenario, the scenarios with high hydrogen maturity are close. In the most optimistic HHH scenario 99.1 % of emissions are cut, and even in the LHL scenario we observe a 96.2 % emission reduction. The only two scenarios where the emission reduction goal in 2030 is not met is LLL and HLL. These are the scenarios where both hydrogen fuel and biofuels are less mature. This indicates that battery electric vehicles cannot handle the demand for sustainable transport, likely because there is no electric long-distance option for sea transport.



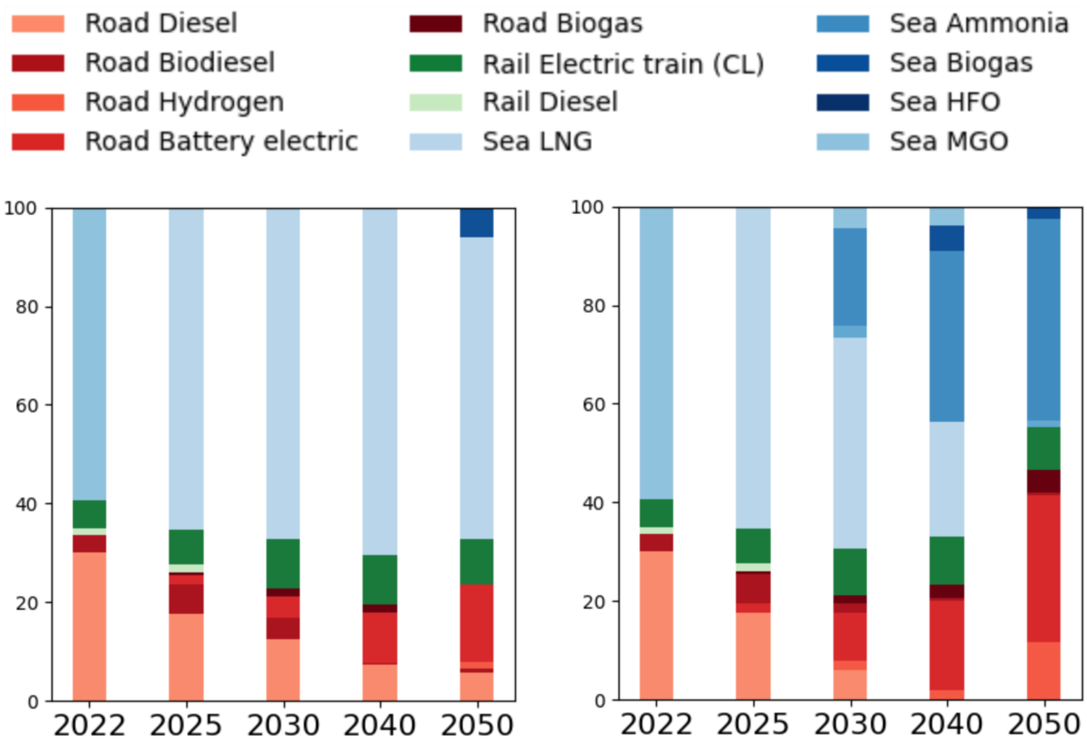
(a) LLL scenario

(b) HHH scenario

Figure 9.3: The mode-fuel mix in two scenarios. The ratios are based on transport in tkm.

Figure 9.3 shows the portion of demand in tonnekilometres covered by each mode-fuel combination for all time periods in the most pessimistic and optimistic maturity scenarios. Of course, the mode-fuel mixes for 2022 and 2025 are identical as they are first stage variables. Expectedly, the use of high emission fuels is much more prevalent in the low maturity scenario where MGO is still very much in use in 2050. In the high maturity scenario biogas is the only CO_2 emitting fuel still in use in 2050. Ammonia is the preferred fuel for sea transport, as it is sustainable and most cost-effective. Note that transport by sea appears to dominate international transport. This is likely because transport by sea has the lowest average costs per tkm. Still, the dominance of sea transport is overexaggerated by Figure 9.3 due to sea being the only mode available for transport to and from the world outside Europe. These distances are considerably longer, which leads to a big impact in tonnekilometres.

If we instead observe domestic transport, where the distances are less extreme, this provides a different perspective. Figure 9.4 shows the mode-fuel mix in tonnekilometres domestically for the same scenarios. Rail and road is used much more inland. Both battery electric and hydrogen on road are preferred over alternatives on sea. However, in the most pessimistic maturity scenario, Norwegian freight transport is still reliant on road diesel and LNG to cover all transport demand in 2050. Even in the most optimistic scenario, HHH, there is some reliance on biogas in 2050.



(a) LLL domestic scenario

(b) HHH domestic scenario

Figure 9.4: The mode-fuel mix domestically in two scenarios. The ratio is based on transport in tkm.

As for the most popular paths, the paths to and from Europe and the remaining world experience the most flow in all time periods. This makes sense as there is much international demand. Almost all the most popular paths use one mode for the entire journey, thus avoiding the extra transfer cost. The most used multimode path goes from origin node Stavanger to transfer node Kristiansand by road, and then by sea to Europe. Several paths like this, with a transfer from road to sea, are used extensively by our model. This could be a solution the model uses to travel by sea as much as possible, even when the origin node's harbour is at capacity.

9.2.1 Comparison to Deterministic Version

In the deterministic version of a stochastic model, all uncertainty is replaced by the expected values of the uncertain parameters. All other parameters remain unchanged, which means that the presence of uncertainty is the only aspects that differentiates the two instances. Then, by comparing the first stage variables of the stochastic solution to the deterministic version, we can learn which decisions are made to mitigate uncertainty. This contributes to a better understanding of how our stochastic solution is affected by uncertainty.

Table 9.3: Objective value and computational time of the deterministic version of the ambitious case.

Instance	Objective value (BNOK)	Objective value excl. penalty (BNOK)	Time (s)	Optimality gap
Deterministic version	76 780.00	235.75	5.0	< 0.01 %

As expected the objective value of the deterministic version, provided in Table 9.3, is lower than the stochastic model as it is based on expected values of maturity and thus does not take into account uncertainty. Overall there is little variation in most decision variables in 2022 and 2025 for the stochastic instance and the deterministic version. The emission limit does not appear to significantly restrict the solution until 2030 and beyond. Thus, mode-fuel mix remains almost identical for both instances before 2030. This also applies to the paths used which stay relatively constant.

For binary decision variables concerning capacity expansions, however, the differences are much more apparent. We can observe from Figure 9.5 that the stochastic model spends considerably more on investments, especially in rail links. Only four investments in rail link expansion are made in 2022 and 2025 the deterministic version, compared to 13 in the stochastic model. This is most likely because the stochastic model takes into account the enormous emission penalties in the LLL and HLL scenarios and tries to make up for it. In the deterministic version, such low maturity levels will never materialize. Investments in infrastructure such as rail link expansions do not go into effect until the time period after investment, so it is necessary to invest in 2025 in order to reduce emissions in 2030.

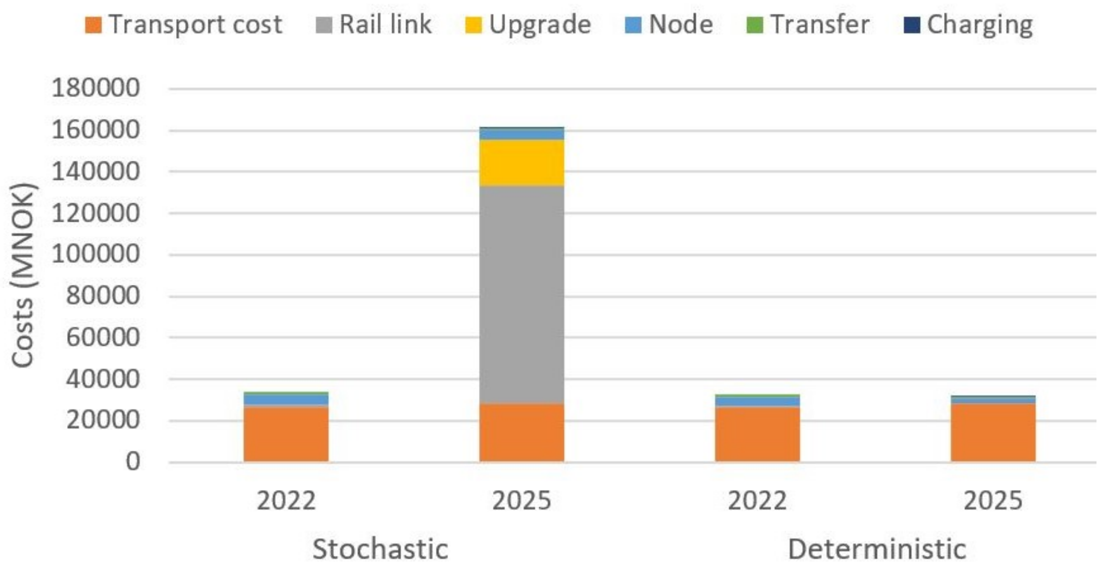


Figure 9.5: The share of total costs attributed to each part of the objective function in the stochastic and deterministic scenarios in the ambitious case.

Table 9.4 breaks down this disparity further. Here we can clearly see the massive investment of 105 277 MNOK in railway lines 2025 in the stochastic version versus no investment in the deterministic version. In fact, the stochastic solution invests in all possible rail link expansions and upgrades. This occurs because rail offers the only zero-emission fuel, contact line, which has no maturity constraint. Rail infrastructure is therefore expanded to the absolute limit in order to hedge against the risk of low maturity in 2030. In the deterministic version on the other hand, a portion of these rail investments are not done until later periods as there is no risk of low maturity in 2030. Capacity investments in harbours stay relatively constant in the two instances. Investments in harbour capacity are actually higher in the deterministic version compared to the stochastic case in 2022. Interestingly, the deterministic version invests 36 MNOK in energy station infrastructure on road. This might be attributed to a higher need for low-emission fuels on road as there is less investment in rail.

Table 9.4: A comparison of the investments made in the stochastic and deterministic instances in the ambitious case. The investment costs are in MNOK.

Investment	**Stochastic**		**Deterministic**	
	2022	2025	2022	2025
Railway lines	1269	105 277	939	0
Rail terminals	2873	3400	1925	1399
Harbours	2353	1366	2993	1319
Railway line upgrade	0	22 009	0	0
Energy station infrastructure	0	197	0	233

Additionally, it is of interest to evaluate how the solution of the deterministic model performs relative to the stochastic program. The VSS, which is calculated based on EEV and RP as presented in Section 5.1, is given in Table 9.5.

Table 9.5: The EEV and RP objective value, and the resulting VSS in BNOK for the ambitious case.

	EEV	**RP**	**VSS**	**VSS (%)**
100% reduction goal	158 937.64	154 783.55	4 154.09	2.61

Solving the RP instead of the stochastic program with the deterministic model's first-stage solutions decreases the total costs by approximately 4 154.09 BNOK. This is equivalent to a 2.61 % improvement of the objective function value. When solving the deterministic model, the first stage solution differs from the first stage solution of the stochastic version. From Figure 9.5 it is apparent that a substantial amount of investments are made in especially railway links compared to the first-stage solution of the deterministic model. This solution performs worse when faced with uncertain maturities in the second stage, as it fails to ensure sufficient infrastructure related investments for adapting well to the case of low maturities for multiple or all fuel groups. This is mostly related to ensuring sufficient capacity in railway links and terminals early on. Infrastructure related expansions for rail and sea are only made available in the subsequent time period, meaning that few investments in both 2022 and 2025, may result in significant emission violations, especially in 2030. The difference in EEV and RP does however not appear too large in this case, as none of the scenarios or the expected value scenario are able to reach the emission reduction target in 2050. This leads to large emission penalty costs which make up most of the objective function value.

9.2.2 Sensitivity Analysis of the Ambitious Instance

Probabilities
In this ambitious instance, each scenario has a 12.5 % probability. To explore if a change in the scenario probabilities will change the solution, we run instances with other probability distributions which are presented in Table 9.6.

Table 9.6: The probability distribution for the scenarios for various probability instances.

Scenario	**Original case**	**Probability High**	**Probability Low**	**Probability LowExtremes**
HHH	12,5 %	10 %	3 %	2 %
HHL	12,5 %	20 %	9 %	16 %
HLH	12,5 %	20 %	9 %	16 %
HLL	12,5 %	9 %	20 %	16 %
LHH	12,5 %	20 %	9 %	16 %
LHL	12,5 %	9 %	20 %	16 %
LLH	12,5 %	9 %	20 %	16 %
LLL	12,5 %	3 %	10 %	2 %

When varying the probabilities, the solution does not change in any significant manner. The investments in railway lines, railway terminals and harbours in stays identical in 2022 and 2025, when compared with the original instance. It is also interesting to note that the probabilities do not affect the investments made in 2030-2050. We observe that the same investments are made in the HHH scenario in the original case of equal probability, as in the HHH scenario with other probability distributions. This is also the case for all other scenarios. The usage of modes and fuels only shows marginal differences when the probabilities change, and thus the investments in charging and filling infrastructure also remains almost unchanged. This indicates that the solution is robust as it does not drastically change with varying parameters. The only noticable difference is that a partial electrification of the railway line between Innlandet and Trøndelag is chosen in the LowExtremes instance, while a full electrification is chosen in the original case and in the low and high probability instances.

Generalized Transportation Costs
A sensitivity analysis was also performed through changing the generalized transportation costs. These were increased and decreased by 25 % for all new fuels, based on estimates

from Martin et al. [2021], while the costs of all conventional fuels remained the same. Changing the costs does not affect the investments made in railway lines, terminals or harbours in 2022 and 2025. As the cost of all new fuels within each mode is changed, varying the costs does not favour any mode in particular. Hence, the distribution between modes remains unchanged and these investments are not affected.

Changing the costs does, however, have an effect on which fuels are used, especially on road. When comparing with the original case, the low cost instance uses 16,5 % less diesel and almost 70 % more biodiesel in 2022. Battery electricity is also used in 2022 in a low cost instance, which is not used at all in 2022 in the model with average costs. As sustainable fuels are more competitive in the low cost instance, a faster introduction of these fuels seems reasonable. When comparing the high cost instance with average cost version, the diesel usage in 2022 increases by 21.6 % and biodiesel is not used at all in 2022. We also observe differences in fuels for sea transport, where around 50 % of the MGO that is used in 2022 in the original case is replaced by LNG in the high cost instance. While these differences are apparent in 2022, the differences in 2025 are minimal. Changing the generalized transportation costs lead to a 7.5 % reduction in the objective value in the low case instance, and an increase of 5.6 % in the high costs instance.

Carbon Price
The carbon price was increased according to Table 8.12 to see if this might affect the solution. An instance with the average generalized transportation costs and high carbon price, yielded a nearly identical solution to the original case. An instance with lower costs and a high carbon price was also tested, and the solution was practically the same as the solution in the low cost and average carbon price instance. Hence, varying the carbon price does not affect the solution in any meaningful way.

Demand
The demand levels shown in Section 8.3 highly affect the feasibility of the problem, as they must always be met. A way to achieve decarbonization of the freight transport sector, in addition to using new sustainable fuels and expanding infrastructure capacity, is to reduce this demand for freight transport. Therefore, it is of interest to investigate how decreased demand affects the solution. A proposed gradual reduction of the forecasted demand levels, where all the demand for all product groups is reduced by the same factor, is given in Table 9.7. The resulting emission reduction levels for the low demand instance are given in Figure 9.6.

Table 9.7: New demand in each time period.

	2022	**2025**	**2030**	**2040**	**2050**
Reduction	0 %	5 %	10 %	25 %	20 %
New demand (million tonnes)	240.9	243.5	247.7	231.4	235.8

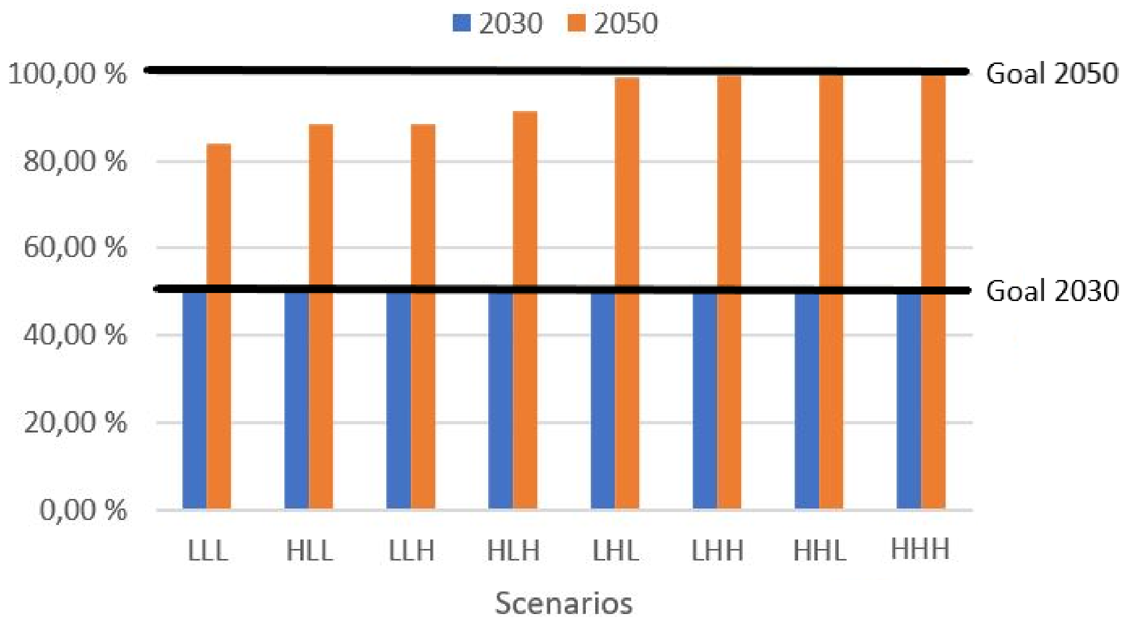


Figure 9.6: The emission reduction in each scenario in the ambitious case with reduced demand. The reduction is given in percentage of the 2022 emission level.

When reducing the demand, the emission reduction goal of 2030 is reached in all scenarios. The emission is also reduced by over 99 % in 2050 in four scenarios. The average emission reduction is 94 % in 2050. These results show that less demand for transportation is important in order to ensure a complete decarbonization of the sector. It should however be noted that it might be challenging to reduce the demand for transportation, especially of product groups that are non-consumer goods.

9.2.3 Summarizing Remarks

No changes in the input parameters discussed changed the solution of the model in a significant manner, except for decrease in demand. It seems that the very large penalty for exceeding the emission constraint overshadows the importance of any other input parameter, as the model will do anything in its power, including most of the possible infrastructure investments, in order to not exceed the constraint more than it has to. Even with extensive investment, Figure 9.6 tells us not even the most optimistic maturity scenario manages to reach zero emissions in 2050 in the ambitious case. If we instead were to reduce the emission constraint to a level where a feasible solution exists for all scenarios, we might get more realistic and interesting results. We proceed with a reduced emission limit to investigate how this affects the results, under the assumption that demand can not be reduced.

9.3 Realistic Case - Reducing the Emission Target to 75 %

To guarantee a feasible solution, the emission limits for years 2030, 2040 and 2050 are relaxed according to the numbers in Table 9.8. These new emission reduction goals are set just below the lowest emission reduction achieved by any scenario in the previous instance. When lowering the emission targets, a 46 % emission reduction in 2030 and 75 % emission reduction in 2050 is achieved in all scenarios. This means the emission violation penalty does not affect the objective value in this case, which we will call the realistic case.

Table 9.8: New emission reduction goal.

Instance	**2030**	**2040**	**2050**
Ambitious case	50 %	75 %	100 %
Realistic case reduction	46 %	64 %	75 %

From Table 9.9, we observe that relaxing the emission reduction goals cuts total costs in half. This signals that achieving the final 14.3 % decrease in emissions in 2050, from a 75 % reduction in the ambitious case to a 89.3 % reduction in the realistic case, requires substantial investments.

Table 9.9: Objective values and computational time for the ambitious and realistic cases.

Instance	**Objective value (BNOK)**	**Time (s)**	**Average reduction 2030**	**Average reduction 2050**
Ambitious case	287.74	24.4	49.5 %	89.3 %
Realistic case	146.33	127.3	46 %	75 %

The cost reductions in the realistic case largely occurs due to substantially less investment in rail. While the model chooses to expand capacity in 13 railway links in 2022 and 2025 in the ambitious case, only three railway lines, Agder-Rogaland, Oslo-Vestland and Oslo-Innlandet, are expanded in the realistic case. Since these lines are expanded in both instances of the model, it seems that they should prioritized in the railway investments made by the Norwegian government. Figure 9.7 emphasizes how much this impacts total costs, as the rail link investments make up about two thirds of total costs in 2025 for the ambitious case. Furthermore, 19 capacity expansions in railway terminals are implemented in the ambitious case during 2022 and 2025. In the realistic case, on the other hand, only three capacity expansions in railway terminals occur in 2022 and 2025. For transport by sea, however, we do not observe this rate of decreased investment. Except for a single harbor investment in Agder, all the same capacity investments in sea harbors are made in 2022 and 2025. This indicates that capacity expansions in sea terminals provide the most cost-effective path to reducing emissions, and that most rail infrastructure is too expensive to expand.

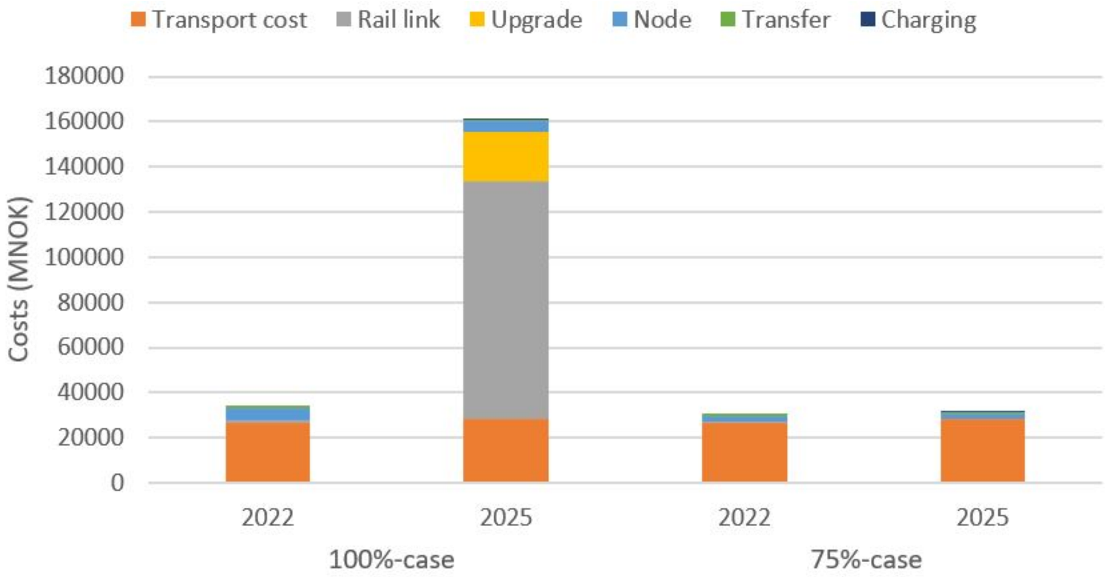
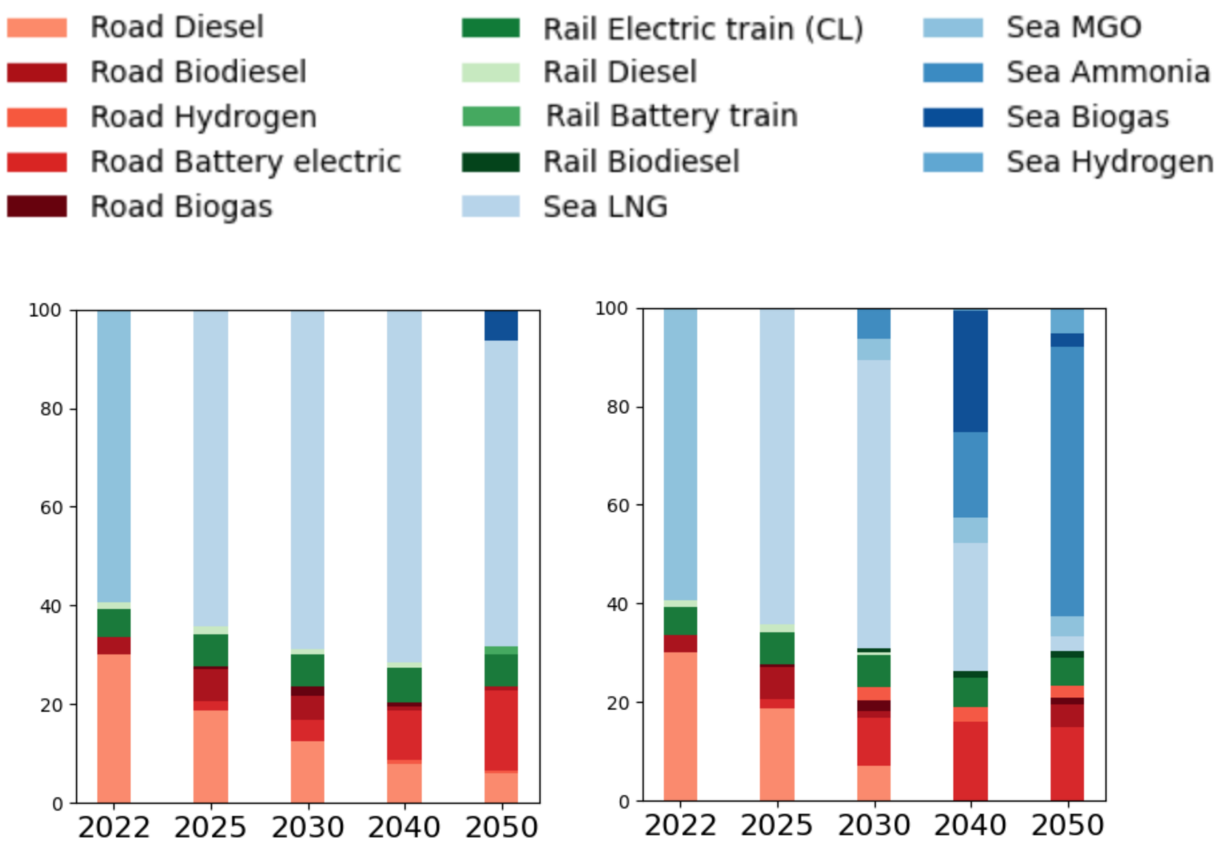


Figure 9.7: The share of total costs attributed to each part of the objective function the ambitious and the realistic instances.

As for the mode-fuel mix domestically for the realistic case, shown in Figure 9.8, the mode mix appears quite similar in Figure 9.4, which shows the same plots for the ambitious case. One exception occurs in the optimistic scenario of the realistic case where sea continues to be dominant in 2050, as opposed to in the ambitious case. Perhaps this is due to cheaper options for sea being more available when the emission constraint is relaxed. Unlike the previous instance, there is now use of both battery trains in 2050 in LLL, and biodiesel trains in several time periods in HHH. This is most likely because no investment in fully electrified railway links are made in this instance. Therefore battery trains and biodiesel trains are preferred over diesel trains for these links because of lower emission factors.



(a) LLL domestic scenario

(b) HHH domestic scenario

Figure 9.8: The mode-fuel mix domestically in the most pessimistic and optimistic maturity scenarios for realistic case. The ratio is based on transport in tkm.

9.3.1 Comparison to the Deterministic Version

Comparing this realistic stochastic instance to the deterministic version shows similar results as in Section 9.2.1. There are strong similarities in most decision variables for 2022 and 2025 for the stochastic instance and the deterministic counterpart. The exception is decisions regarding capacity expansions as they are the only variables which have a direct impact on the next time period. This is due to the fact that these binary variables only allow for increased capacity in the time period after they are invested in.

Table 9.10: A comparison of the investments made in the stochastic and deterministic version for the realistic case. The investment costs are in MNOK.

Investment	**Stochastic**		**Deterministic**	
	2022	2025	2022	2025
Railway lines	791	0	0	0
Rail terminals	737	527	0	0
Harbours	1602	2082	1602	1896
Railway line upgrade	0	0	0	0
Energy station infrastructure	0	223	0	226

Consequently, the most striking difference between the stochastic instance and the deterministic version is in the number of capacity investments made, especially for rail. An overview of investment costs in infrastructure in 2022 and 2025 for both versions is presented in Figure 9.9. In the stochastic instance, three railway terminals are expanded in 2022 and 2025 at a total cost of 1.3 BNOK. In the deterministic version, no capacity expansion investments in rail links are made at any time period. The same goes for rail terminals, where three rail terminals are expanded in the stochastic instance, while zero rail terminal expansions are made in the deterministic version. These differences in capacity investments appear to only affect the railway network. For sea, capacity investments in harbour are made almost at the same rate in the stochastic and deterministic model, as Table 9.10 reflects.

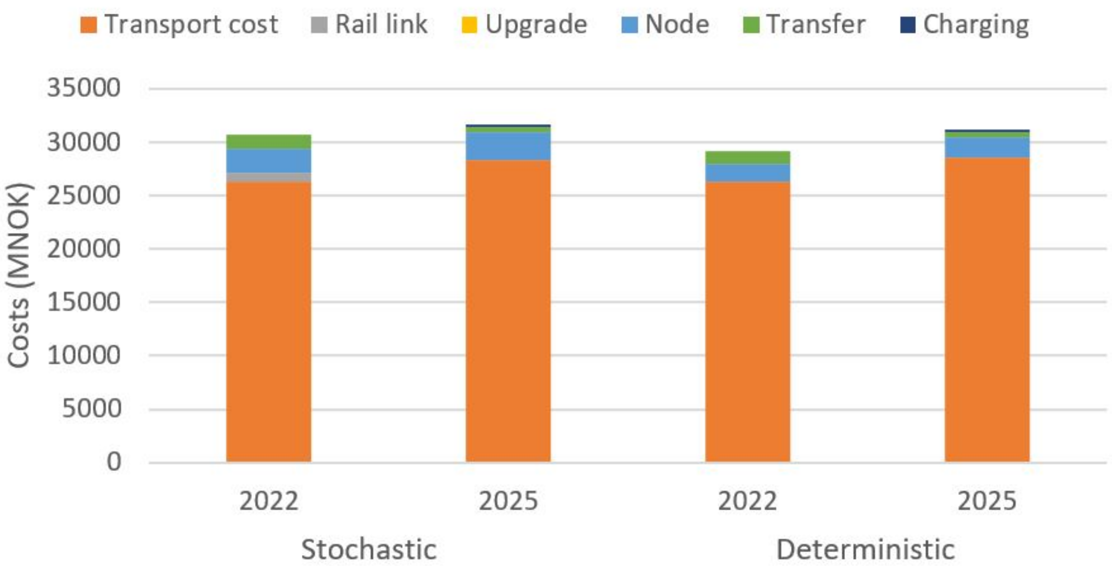


Figure 9.9: The share of total costs attributed to each part of the objective function in the stochastic and deterministic instances for the realistic case.

The EEV, RP and VSS is reported for the realistic case in Table 9.11. The VSS shows that the stochastic model improves the solution with 146.33 BNOK, or 88.39%, compared to the EEV. As seen in Figure 9.9, more investments are made in increasing rail and sea capacities in the first-stage time periods in the stochastic version compared to the deterministic counterpart. The added flexibility from investing in rail in particular results in a better objective function value when facing the uncertain maturity development for the new fuels in the second stage. The difference between the EEV and RP values is more substantial in the realistic case than in the ambitious case. This is largely due to the fact that the emission violation penalty cost is lower when the emission reduction goal is reduced. Emission penalty costs does, for that reason, make up a smaller or non-existent amount of the objective function values. In fact, emission violation only appears in 2030 for the LLL scenario when the first-stage deterministic model solutions is evaluated in the stochastic version. As explained in Section 9.2.1 this happens because of a lack of sufficient capacity investments in railway lines and terminals in the first-stage. This makes the emission reduction goal for 2030 impossible to reach when a LLL maturity scenario is realized for the new fuels. This outcome highlights the value of hedging against uncertainty, as emission violations are avoided entirely in the stochastic version of the realistic case. The positive VSS indicates a need for a stochastic approach in network design for the Norwegian freight transport modelling in order to adapt well to an uncertain future.

It should be noted that the magnitude of the EEV, and consequently the VSS, is dependent on the value of the emission penalty. A lower emission penalty would reduce the costs of violating the emission limit in 2030 for the LLL case, which would lead to a lower VSS. Hence, the magnitude of the VSS is not necessarily an accurate measure of the actual expected improvement of using a stochastic approach.

Table 9.11: The EEV and RP objective value and the resulting VSS for the realistic case. The values are noted in BNOK.

	EEV	**RP**	**VSS**	**VSS (%)**
Realistic case	1 260.18	146.33	1 113.85	88.39

9.3.2 Sensitivity Analysis in the Realistic Case

Probabilities

When changing the probabilities according to Table 9.6, no changes in investments in railway lines, terminals or harbours occur when comparing to the initial realistic case. The largest differences are found in which fuels are chosen on road. In the high probability case, less biogas and slightly more battery electricity is chosen in 2025. In the high and low extremes probability cases, more biogas is used in 2025. These changes are also seen in the charging and filling infrastructure investments in 2025, where biogas filling on the roads between Trøndelag and Innlandet and between Vestland and Rogaland are affected. For battery electric charging, the road stretches Trøndelag-Nordland and Innlandet-Møre og Romsdal are affected by the changing probabilities. As our solution only changes minimally when we vary the probabilities, we can conclude that our results are robust against uncertainty in probabilities. This must be considered a positive result, as determining realistic probabilities for scenarios is difficult. Therefore, it strengthens the validity of the results that these probabilities do not matter that much in terms of the optimal solution.

Costs

Again, the generalized transportation costs were varied with a 25 % lower and higher case for all new fuels. In the lower case we observe a 7.5 % decrease in the objective function value compared to the original realistic case, while for the higher case the objective value is 5.6 %. This is identical to the change noted in the ambitious case when changing the transportation costs. The change in the solution is also nearly identical to the one observed in the ambitious case. The carbon price increase also does not affect the solution in any noticeable fashion. Hence, we can also conclude that our solution is also robust against uncertainty in cost estimates.

Chapter 10

Concluding Remarks and Further Research

The purpose of this thesis is to gain insight into how the Norwegian freight transport sector can transition to achieve zero-emissions in 2050. In accordance to the Paris Agreement, Norway has committed to reducing emissions significantly by 2030 and becoming a low-emission society by 2050. To reach this goal, investments in new, sustainable fuels and related infrastructure must be made. As emissions must be cut in half by the next eight years, investment decisions for an uncertain future must be made now. Thus, insight into what fuels the Norwegian government should accommodate, and when and where infrastructure investments should be made, is of great importance. We aim to provide some answers to these questions which can help shape environmental policy.

In response to these challenges, we present a two-stage stochastic model that captures the uncertainty of availability of new, sustainable fuels. The objective is to minimize total system costs while meeting all demand and complying with emission reduction limits which gradually get stricter. Various infrastructure investments can be made at each time period to expand the capacity of modes and sustainable fuel options at specific locations.

Our results indicate that if we continue on this trajectory, a zero-emission freight transport sector by 2050 is not achievable. This is mainly due to maturity of sustainable fuels being too low to cover all demand. Even with substantial capacity expansions in rail and sea, emissions are still only reduced by 89.3 % in 2050. It is of note that if we were to reduce demand by 20 %, the emission reduction goals are achieved for all scenarios in 2030, and the average emission reduction rises to 94 % in 2050.

If we reduce the emission goal in 2050 from 100 % reduction to 75 % in order to get a feasible solution for all scenarios, we obtain some interesting insights. Like in the ambitious case, the more realistic case favours transport by sea both internationally and domestically. Ammonia is favored as the most cost-effective new fuel for sea transport. The model undergoes harbour expansion investments to a cost of 3.7 billion NOK in 2022 and 2025. However, the stochastic model also invests heavily in rail infrastructure. It is deemed favorable by the model to make large rail infrastructure investments already in 2022 and 2025 to account for the uncertainty in future time periods. This behaviour is not present in the deterministic version. This indicates that capturing the uncertainty of this problem with a stochastic approach actually leads to new and better solutions. The value of this strategy is reflected in the positive VSS which determines that a stochastic approach is important when trying to obtain a flexible solution compared to the deterministic perspective. Thus taking uncertainty into account is quantifiably significant. Additionally, the optimal solution to the stochastic instance appears to be robust against changes in the probabilities assigned to scenarios and variations in costs. This strengthens the validity of our results, as the solution is not dependent on parameters that are hard to estimate.

Complete decarbonization of Norwegian freight transport by 2050 may not be obtainable, but efforts can be made to drastically reduce emissions. In the majority of scenarios, reducing emissions by half in 2030 is achievable. Our results indicate that, on one hand, the Norwegian government should emphasise sea transport, with ammonia as a particularly promising new fuel. On the other hand, investing extensively in rail lines and terminals can ensure added flexibility no matter which fuel groups turn out to become widely available.

While our model covers a lot of ground, there is more insight to be gained by extending the model further. One area of further work entails including more stochasticity in the model. As of now, maturity developments of fuels is the only stochastic element. It could be interesting to include some parameters from our sensitivity analysis in the stochastic model itself, like carbon prices and new fuel costs. Furthermore, interesting results can be obtained from varying the emission penalty which reflects the trade-off between emission reduction and total system cost. With a lower emission penalty it would be possible to investigate how the solution changes when maximum possible compliance with the emission limit is not enforced. Conducting a sensitivity analysis on the investments costs could also be of interest. Investment costs for infrastructure with a very long economic lifetime are hard to estimate accurately, and the costs are likely to affect the solution as they are usually very high.

Finally, we have as of now only tested two-stage instances of our model. We believe, however, that the problem structure is well suited for a multi-stage formulation, as maturity realizations get more certain the closer we are to the time period where the uncertainty lies. A multi-stage problem in combination with possibly added stochastic parameters, as described above, would make the model more computationally difficult to solve. This could make the progressive hedging algorithm useful in terms of computation time.

A multi-stage formulation may provide more realistic solutions to our problem, than our current two-stage approach where we learn the maturity of fuels in 2050, already in 2030. For the multi-stage formulation to be effective, however, we require estimates that realistically represent the maturity of each new fuel, in terms of fuel feasibility, scalability and cost-effectiveness until 2050. These estimates turned out to be the hardest to obtain when collecting data. To which extent the emission goals for 2030 and 2050 are met, greatly depends on these maturity estimates. Consequently setting these parameters to a realistic level becomes even more central and should be an area of further investigation.

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Appendix

A Proof of Valid Lower Bounds

Gade et al. [2016] presented the following proof that the lower bounds can be computed as shown in Section 5.2.1 under the same assumptions:

Let $(\hat{\hat{x}}, \{(\bar{x}(\xi), \bar{y}(\xi)), \forall \xi \in \Xi\})$ be an optimal solution to the SMIP defined in Section 5.2.1. Feasibility implies that $(\bar{x}(\xi), \bar{y}(\xi)) \in X(\xi)$ for each $\xi \in \Xi$. Thus:

$$D_\xi(\omega(\xi)) \leq c^\top \bar{x}(\xi) + g(\xi)^\top \bar{y}(\xi) + \omega(\xi)^\top \bar{x}(\xi). \tag{1}$$

Then

$$\begin{aligned} D(\omega) &\leq \sum_{\xi \in \Xi} p_\xi (c^\top \bar{x}(\xi) + g(\xi)^\top \bar{y}(\xi) + \omega(\xi)^\top \bar{x}(\xi)) \\ &= \sum_{\xi \in \Xi} p_\xi (c^\top \hat{\hat{x}} + g(\xi)^\top \bar{y}(\xi)) + \sum_{\xi \in \Xi} p_\xi \omega(\xi)^\top \hat{\hat{x}} \\ &= \sum_{\xi \in \Xi} p_\xi (c^\top \hat{\hat{x}} + g(\xi)^\top \bar{y}(\xi)) = z^*. \end{aligned} \tag{2}$$

B Modes and Vehicles

Table 1: An overview of which vehicles can be used to transport which product groups.

Mode	Fuel	Dry bulk	Wet bulk	Fish	General cargo	Industrial	Thermo	Timber
Road	Dry bulk truck	x						
	Articulated semi, containers				x			
	Thermo truck			x			x	
	Articulated semi, closed					x		
	Timber truck with hanger							x
	Tank truck distance		x					
Sea	Dry bulk 9000 dwt	x						
	Container lo/lo 8500 dwt			x	x		x	
	Break bulk lo/lo 2500 dwt					x		x
	Tanker vessel 17000 dwt		x					
Rail	System trains (dry bulk)	x						
	Combi trains			x	x	x	x	
	Timber trains							x
	System trains (wet bulk)		x					

Table 2: The capacity in tonnes for all vehicles. From Grønland [2018].

Mode	**Vehicle**	**Capacity (tonnes)**
Road	Articulated semi, closed	33
	Articulated semi, containers	33
	Tank truck distance	33
	Dry bulk truck	18.4
	Timber truck with hanger	34
	Termo truck	33
Sea	Container lo/lo 8500 dwt	8500
	Break bulk lo/lo 2500 dwt	2500
	Dry bulk 9000 dwt	9000
	Tanker vessel 17 000 dwt	17 000

Table 3: The possible modes for all node pairs. Ro = Road, S = Sea, Ra = Rail.

	Oslo/Viken	Innlandet	Vestfold og Telemark	Agder	Rogaland	Vestland	Møre og Romsdal	Trøndelag	Nordland	Troms og Finnmark	Sør-Sverige	Nord-Sverige	Europa	Verden	Kontinental-sokkelen
Oslo/Viken															
Innlandet	Ro, Ra														
Vestfold og Telemark	Ro, S, Ra														
Agder	S		Ro, S, Ra												
Rogaland	S		S	Ro, S, Ra											
Vestland	Ro, S, Ra		S	S	Ro, S										
Møre og Romsdal	S	Ro, Ra	S	S	S	Ro, S									
Trøndelag	S	Ro, Ra	S	S	S	S	Ro, S								
Nordland	S		S	S	S	S	S	Ro, S, Ra							
Troms og Finnmark	S		S	S	S	S	S	S	Ro, S, Ra						
Sør-Sverige	Ro, S, Ra	Ra	S	S	S	S	S	S	S	S					
Nord-Sverige	S		S	S	S	S	S	Ro, S, Ra	Ro, S, Ra	S	Ro, S, Ra				
Europa	S		S	S	S	S	S	S	S	S	Ro, S, Ra	S			
Verden	S		S	S	S	S	S	S	S	S	S	S	S		
Kontinental-sokkelen	S		S	S	S	S	S	S	S	S	S	S	S	S	

C Generalized Transportation Costs

The following table contain the costs of all combinations of mode, product group (vehicle), fuel and year. The costs are given in NOK/tkm. The numbers marked in blue were provided by Martin et al. [2021], and the remaining numbers are estimated based on relative costs. Battery train refers to battery trains utilized on partial electrified railway lines and electric trains are trains with CL-technology.

Table 4: The generalized transportation costs for all combinations of mode, fuel and vehicle/product group for all time periods. Given in NOK/tkm.

Mode	**Product group**	**Fuel**	**2022**	**2025**	**2030**	**2040**	**2050**
Road	Dry bulk	Diesel	0.6589	0.6584	0.6584	0.6584	0.6579
Road	Dry bulk	Battery electric	0.8566	0.6782	0.5991	0.5596	0.5460
Road	Dry bulk	Hydrogen	1.0731	0.9367	0.8338	0.7395	0.7085
Road	Dry bulk	Biodiesel	0.6985	0.7308	0.7440	0.7572	0.7697
Road	Dry bulk	Biogas	0.7380	0.7440	0.7374	0.7308	0.7237
Road	General cargo	Diesel	0.3674	0.3671	0.3671	0.3671	0.3668
Road	General cargo	Battery electric	0.4776	0.3781	0.3341	0.3120	0.3045
Road	General cargo	Hydrogen	0.5983	0.5223	0.4649	0.4123	0.3950
Road	General cargo	Biodiesel	0.3894	0.4075	0.4148	0.4222	0.4292
Road	General cargo	Biogas	0.4115	0.4148	0.4112	0.4075	0.4035
Road	Fish	Diesel	0.3674	0.3671	0.3671	0.3671	0.3668
Road	Fish	Battery electric	0.4776	0.3781	0.3341	0.3120	0.3045
Road	Fish	Hydrogen	0.5983	0.5223	0.4649	0.4123	0.3950
Road	Fish	Biodiesel	0.3894	0.4075	0.4148	0.4222	0.4292
Road	Fish	Biogas	0.4115	0.4148	0.4112	0.4075	0.4035
Road	Thermo	Diesel	0.3674	0.3671	0.3671	0.3671	0.3668
Road	Thermo	Battery electric	0.4776	0.3781	0.3341	0.3120	0.3045
Road	Thermo	Hydrogen	0.5983	0.5223	0.4649	0.4123	0.3950
Road	Thermo	Biodiesel	0.3894	0.4075	0.4148	0.4222	0.4292
Road	Thermo	Biogas	0.4115	0.4148	0.4112	0.4075	0.4035
Road	Industrial goods	Diesel	0.3674	0.3671	0.3671	0.3671	0.3668
Road	Industrial goods	Battery electric	0.4776	0.3781	0.3341	0.3120	0.3045
Road	Industrial goods	Hydrogen	0.5983	0.5223	0.4649	0.4123	0.3950
Road	Industrial goods	Biodiesel	0.3894	0.4075	0.4148	0.4222	0.4292
Road	Industrial goods	Biogas	0.4115	0.4148	0.4112	0.4075	0.4035
Road	Timber	Diesel	0.3566	0.3563	0.3563	0.3563	0.3560
Road	Timber	Battery electric	0.4636	0.3670	0.3242	0.3029	0.2955
Road	Timber	Hydrogen	0.5807	0.5069	0.4513	0.4002	0.3834
Road	Timber	Biodiesel	0.3780	0.3955	0.4026	0.4098	0.4166
Road	Timber	Biogas	0.3994	0.4026	0.4026	0.3955	0.3916
Road	Wet bulk	Diesel	0.3674	0.3671	0.3671	0.3671	0.3668
Road	Wet bulk	Battery electric	0.4776	0.3781	0.3341	0.3120	0.3045
Road	Wet bulk	Hydrogen	0.5983	0.5223	0.4649	0.4123	0.3950
Road	Wet bulk	Biodiesel	0.3894	0.4075	0.4148	0.4222	0.4292
Road	Wet bulk	Biogas	0.4115	0.4148	0.4112	0.4075	0.4035

Mode	Product group	Fuel	2022	2025	2030	2040	2050
Sea	Dry bulk	HFO	0.0749	0.0748	0.0748	0.0747	0.0747
Sea	Dry bulk	MGO	0.0824	0.0823	0.0823	0.0822	0.0821
Sea	Dry bulk	LNG	0.0882	0.0881	0.0880	0.0879	0.0879
Sea	Dry bulk	Hydrogen	9999	9999	0.1625	0.1316	0.1080
Sea	Dry bulk	Ammonia	9999	9999	0.1571	0.1302	0.1053
Sea	Dry bulk	Biodiesel	0.0989	0.1004	0.1020	0.1036	0.1051
Sea	Dry bulk	Biogas	0.1038	0.1055	0.1071	0.1087	0.1104
Sea	General cargo	HFO	0.0793	0.0793	0.0792	0.0791	0.0791
Sea	General cargo	MGO	0.0873	0.0872	0.0871	0.0870	0.0870
Sea	General cargo	LNG	0.0934	0.0933	0.0932	0.0931	0.0930
Sea	General cargo	Hydrogen	9999	9999	0.1721	0.1394	0.1144
Sea	General cargo	Ammonia	9999	9999	0.1664	0.1379	0.1115
Sea	General cargo	Biodiesel	0.1047	0.1064	0.1080	0.1097	0.1113
Sea	General cargo	Biogas	0.1100	0.1117	0.1134	0.1151	0.1169
Sea	Fish	HFO	0.0793	0.0793	0.0792	0.0791	0.0791
Sea	Fish	MGO	0.0873	0.0872	0.0871	0.0870	0.0870
Sea	Fish	LNG	0.0934	0.0933	0.0932	0.0931	0.0930
Sea	Fish	Hydrogen	9999	9999	0.1721	0.1394	0.1144
Sea	Fish	Ammonia	9999	9999	0.1664	0.1379	0.1115
Sea	Fish	Biodiesel	0.1047	0.1064	0.1080	0.1097	0.1113
Sea	Fish	Biogas	0.1100	0.1117	0.1134	0.1151	0.1169
Sea	Thermo	HFO	0.0793	0.0793	0.0792	0.0791	0.0791
Sea	Thermo	MGO	0.0873	0.0872	0.0871	0.0870	0.0870
Sea	Thermo	LNG	0.0934	0.0933	0.0932	0.0931	0.0930
Sea	Thermo	Hydrogen	9999	9999	0.1721	0.1394	0.1144
Sea	Thermo	Ammonia	9999	9999	0.1664	0.1379	0.1115
Sea	Thermo	Biodiesel	0.1047	0.1064	0.1080	0.1097	0.1113
Sea	Thermo	Biogas	0.1100	0.1117	0.1134	0.1151	0.1169
Sea	Industrial goods	HFO	0.2697	0.2695	0.2693	0.2690	0.2688
Sea	Industrial goods	MGO	0.2967	0.2964	0.2962	0.2959	0.2957
Sea	Industrial goods	LNG	0.3175	0.3171	0.3169	0.3166	0.3164
Sea	Industrial goods	Hydrogen	9999	9999	0.5850	0.4739	0.3889
Sea	Industrial goods	Ammonia	9999	9999	0.5656	0.4688	0.3792
Sea	Industrial goods	Biodiesel	0.3561	0.3616	0.3673	0.3728	0.3784
Sea	Industrial goods	Biogas	0.3739	0.3797	0.3856	0.3915	0.3974
Sea	Timber	HFO	0.2697	0.2695	0.2693	0.2690	0.2688
Sea	Timber	MGO	0.2967	0.2964	0.2962	0.2959	0.2957
Sea	Timber	LNG	0.3175	0.3171	0.3169	0.3166	0.3164
Sea	Timber	Hydrogen	9999	9999	0.5850	0.4739	0.3889
Sea	Timber	Ammonia	9999	9999	0.5656	0.4688	0.3792
Sea	Timber	Biodiesel	0.3561	0.3616	0.3673	0.3728	0.3784
Sea	Timber	Biogas	0.3739	0.3797	0.3856	0.3915	0.3974
Sea	Wet bulk	HFO	0.0397	0.0396	0.0396	0.0396	0.0395
Sea	Wet bulk	MGO	0.0436	0.0436	0.0436	0.0435	0.0435
Sea	Wet bulk	LNG	0.0467	0.0466	0.0466	0.0466	0.0465
Sea	Wet bulk	Hydrogen	9999	9999	0.0860	0.0697	0.0572
Sea	Wet bulk	Ammonia	9999	9999	0.0832	0.0689	0.0558
Sea	Wet bulk	Biodiesel	0.0524	0.0532	0.0540	0.0548	0.0557
Sea	Wet bulk	Biogas	0.0550	0.0558	0.0567	0.0576	0.0584

Mode	Product group	Fuel	2022	2025	2030	2040	2050
Rail	Dry bulk	Diesel	0.1387	0.1387	0.1387	0.1387	0.1387
Rail	Dry bulk	Electric train	0.1156	0.1156	0.1156	0.1156	0.1156
Rail	Dry bulk	Hybrid	0.1525	0.1525	0.1525	0.1525	0.1525
Rail	Dry bulk	Battery train	0.1664	0.1636	0.1609	0.1567	0.1525
Rail	Dry bulk	Hydrogen	0.2773	0.2496	0.2219	0.1941	0.1733
Rail	Dry bulk	Biodiesel	0.1456	0.1470	0.1484	0.1498	0.1512
Rail	General cargo	Diesel	0.1965	0.1965	0.1965	0.1965	0.1965
Rail	General cargo	Electric train	0.1637	0.1637	0.1637	0.1637	0.1637
Rail	General cargo	Hybrid	0.2161	0.2161	0.2161	0.2161	0.2161
Rail	General cargo	Battery train	0.2357	0.2318	0.2279	0.2220	0.2161
Rail	General cargo	Hydrogen	0.3929	0.3536	0.3143	0.2750	0.2456
Rail	General cargo	Biodiesel	0.2063	0.2082	0.2102	0.2122	0.2141
Rail	Fish	Diesel	0.1965	0.1965	0.1965	0.1965	0.1965
Rail	Fish	Electric train	0.1637	0.1637	0.1637	0.1637	0.1637
Rail	Fish	Hybrid	0.2161	0.2161	0.2161	0.2161	0.2161
Rail	Fish	Battery train	0.2357	0.2318	0.2279	0.2220	0.2161
Rail	Fish	Hydrogen	0.3929	0.3536	0.3143	0.2750	0.2456
Rail	Fish	Biodiesel	0.2063	0.2082	0.2102	0.2122	0.2141
Rail	Thermo	Diesel	0.1965	0.1965	0.1965	0.1965	0.1965
Rail	Thermo	Electric train	0.1637	0.1637	0.1637	0.1637	0.1637
Rail	Thermo	Hybrid	0.2161	0.2161	0.2161	0.2161	0.2161
Rail	Thermo	Battery train	0.2357	0.2318	0.2279	0.2220	0.2161
Rail	Thermo	Hydrogen	0.3929	0.3536	0.3143	0.2750	0.2456
Rail	Thermo	Biodiesel	0.2063	0.2082	0.2102	0.2122	0.2141
Rail	Industrial goods	Diesel	0.1965	0.1965	0.1965	0.1965	0.1965
Rail	Industrial goods	Electric train	0.1637	0.1637	0.1637	0.1637	0.1637
Rail	Industrial goods	Hybrid	0.2161	0.2161	0.2161	0.2161	0.2161
Rail	Industrial goods	Battery train	0.2357	0.2318	0.2279	0.2220	0.2161
Rail	Industrial goods	Hydrogen	0.3929	0.3536	0.3143	0.2750	0.2456
Rail	Industrial goods	Biodiesel	0.2063	0.2082	0.2102	0.2122	0.2141
Rail	Timber	Diesel	0.1965	0.1965	0.1965	0.1965	0.1965
Rail	Timber	Electric train	0.1637	0.1637	0.1637	0.1637	0.1637
Rail	Timber	Hybrid	0.2161	0.2161	0.2161	0.2161	0.2161
Rail	Timber	Battery train	0.2357	0.2318	0.2279	0.2220	0.2161
Rail	Timber	Hydrogen	0.3929	0.3536	0.3143	0.2750	0.2456
Rail	Timber	Biodiesel	0.2063	0.2082	0.2102	0.2122	0.2141
Rail	Wet bulk	Diesel	0.1733	0.1733	0.1733	0.1733	0.1733
Rail	Wet bulk	Electric train	0.1445	0.1445	0.1445	0.1445	0.1445
Rail	Wet bulk	Hybrid	0.1907	0.1907	0.1907	0.1907	0.1907
Rail	Wet bulk	Battery train	0.2080	0.2045	0.2011	0.1959	0.1907
Rail	Wet bulk	Hydrogen	0.3467	0.3120	0.2773	0.2427	0.2167
Rail	Wet bulk	Biodiesel	0.1820	0.1837	0.1855	0.1872	0.1889

D Emission Factors

Table 5: The emission factors in a well-to-wheel perspective for all combinations of mode, fuel and product group (vehicle) for all time periods. The emissions are given in gCO_2/tkm.

Mode	**Product group**	**Fuel**	**2022**	**2025**	**2030**	**2040**	**2050**
Road	Dry bulk	Diesel	69.24	67.80	65.46	61.02	56.88
Road	Dry bulk	Battery electric	0	0	0	0	0
Road	Dry bulk	Hydrogen	0	0	0	0	0
Road	Dry bulk	Biodiesel	9.35	9.15	8.84	8.24	7.68
Road	Dry bulk	Biogas	8.48	8.30	8.01	7.47	6.96
Road	General cargo	Diesel	38.61	37.80	36.50	34.02	31.71
Road	General cargo	Battery electric	0	0	0	0	0
Road	General cargo	Hydrogen	0	0	0	0	0
Road	General cargo	Biodiesel	5.21	5.10	4.93	4.59	4.28
Road	General cargo	Biogas	4.73	4.63	4.47	4.17	3.88
Road	Fish	Diesel	38.61	37.80	36.50	34.02	31.71
Road	Fish	Battery electric	0	0	0	0	0
Road	Fish	Hydrogen	0	0	0	0	0
Road	Fish	Biodiesel	5.21	5.10	4.93	4.59	4.28
Road	Fish	Biogas	4.73	4.63	4.47	4.17	3.88
Road	Thermo	Diesel	38.61	37.80	36.50	34.02	31.71
Road	Thermo	Battery electric	0	0	0	0	0
Road	Thermo	Hydrogen	0	0	0	0	0
Road	Thermo	Biodiesel	5.21	5.10	4.93	4.59	4.28
Road	Thermo	Biogas	4.73	4.63	4.47	4.17	3.88
Road	Industrial goods	Diesel	38.61	37.80	36.50	34.02	31.71
Road	Industrial goods	Battery electric	0	0	0	0	0
Road	Industrial goods	Hydrogen	0	0	0	0	0
Road	Industrial goods	Biodiesel	5.21	5.10	4.93	4.59	4.28
Road	Industrial goods	Biogas	4.73	4.63	4.47	4.17	3.88
Road	Timber	Diesel	37.47	36.69	35.42	33.02	30.78
Road	Timber	Battery electric	0	0	0	0	0
Road	Timber	Hydrogen	0	0	0	0	0
Road	Timber	Biodiesel	5.06	4.95	4.78	4.46	4.16
Road	Timber	Biogas	4.59	4.49	4.34	4.04	3.77
Road	Wet bulk	Diesel	38.61	37.80	36.50	34.02	31.71
Road	Wet bulk	Battery electric	0	0	0	0	0
Road	Wet bulk	Hydrogen	0	0	0	0	0
Road	Wet bulk	Biodiesel	5.21	5.10	4.93	4.59	4.28
Road	Wet bulk	Biogas	4.73	4.63	4.47	4.17	3.88

Mode	Product group	Fuel	2022	2025	2030	2040	2050
Sea	Dry bulk	HFO	13.00	12.73	12.29	11.46	10.68
Sea	Dry bulk	MGO	12.09	11.59	10.80	9.39	8.16
Sea	Dry bulk	LNG	9.10	8.72	8.13	7.07	6.14
Sea	Dry bulk	Hydrogen	0	0	0	0	0
Sea	Dry bulk	Ammonia	0	0	0	0	0
Sea	Dry bulk	Biodiesel	11.70	11.22	10.46	9.09	7.89
Sea	Dry bulk	Biogas	3.12	2.99	2.79	2.42	2.11
Sea	General cargo	HFO	27.00	26.44	25.52	23.79	22.18
Sea	General cargo	MGO	25.11	24.07	22.44	19.50	16.94
Sea	General cargo	LNG	18.90	18.12	16.89	14.68	12.75
Sea	General cargo	Hydrogen	0	0	0	0	0
Sea	General cargo	Ammonia	0	0	0	0	0
Sea	General cargo	Biodiesel	24.30	23.30	21.72	18.87	16.40
Sea	General cargo	Biogas	6.48	6.21	5.79	5.03	4.37
Sea	Fish	HFO	27.00	26.44	25.52	23.79	22.18
Sea	Fish	MGO	25.11	24.07	22.44	19.50	16.94
Sea	Fish	LNG	18.90	18.12	16.89	14.68	12.75
Sea	Fish	Hydrogen	0	0	0	0	0
Sea	Fish	Ammonia	0	0	0	0	0
Sea	Fish	Biodiesel	24.30	23.30	21.72	18.87	16.40
Sea	Fish	Biogas	6.48	6.21	5.79	5.03	4.37
Sea	Thermo	HFO	27.00	26.44	25.52	23.79	22.18
Sea	Thermo	MGO	25.11	24.07	22.44	19.50	16.94
Sea	Thermo	LNG	18.90	18.12	16.89	14.68	12.75
Sea	Thermo	Hydrogen	0	0	0	0	0
Sea	Thermo	Ammonia	0	0	0	0	0
Sea	Thermo	Biodiesel	24.30	23.30	21.72	18.87	16.40
Sea	Thermo	Biogas	6.48	6.21	5.79	5.03	4.37
Sea	Industrial goods	HFO	17.50	17.14	16.54	15.42	14.38
Sea	Industrial goods	MGO	16.28	15.60	14.54	12.64	10.98
Sea	Industrial goods	LNG	12.25	11.74	10.95	9.51	8.27
Sea	Industrial goods	Hydrogen	0	0	0	0	0
Sea	Industrial goods	Ammonia	0	0	0	0	0
Sea	Industrial goods	Biodiesel	15.75	15.10	14.08	12.23	10.63
Sea	Industrial goods	Biogas	4.20	4.03	3.75	3.26	2.83
Sea	Timber	HFO	17.50	17.14	16.54	15.42	14.38
Sea	Timber	MGO	16.28	15.60	14.54	12.64	10.98
Sea	Timber	LNG	12.25	11.74	10.95	9.51	8.27
Sea	Timber	Hydrogen	0	0	0	0	0
Sea	Timber	Ammonia	0	0	0	0	0
Sea	Timber	Biodiesel	15.75	15.10	14.08	12.23	10.63
Sea	Timber	Biogas	4.20	4.03	3.75	3.26	2.83
Sea	Wet bulk	HFO	13.60	13.32	12.86	11.98	11.17
Sea	Wet bulk	MGO	12.65	12.13	11.30	9.82	8.53
Sea	Wet bulk	LNG	9.52	9.13	8.51	7.39	6.42
Sea	Wet bulk	Hydrogen	0	0	0	0	0
Sea	Wet bulk	Ammonia	0	0	0	0	0
Sea	Wet bulk	Biodiesel	12.24	11.73	10.94	9.51	8.26
Sea	Wet bulk	Biogas	3.26	3.13	2.92	2.53	2.20

Mode	Product group	Fuel	2022	2025	2030	2040	2050
Rail	Dry bulk	Diesel	18.80	18.41	17.77	16.57	15.44
Rail	Dry bulk	Electric train (CL)	0	0	0	0	0
Rail	Dry bulk	Hybrid	13.16	12.62	11.76	10.22	8.88
Rail	Dry bulk	Battery train	0	0	0	0	0
Rail	Dry bulk	Hydrogen	0	0	0	0	0
Rail	Dry bulk	Biodiesel	3.76	3.60	3.36	2.92	2.54
Rail	General cargo	Diesel	17.90	17.53	16.92	15.77	14.70
Rail	General cargo	Electric train (CL)	0	0	0	0	0
Rail	General cargo	Hybrid	12.53	12.01	11.20	9.73	8.45
Rail	General cargo	Battery train	0	0	0	0	0
Rail	General cargo	Hydrogen	0	0	0	0	0
Rail	General cargo	Biodiesel	3.58	3.43	3.20	2.78	2.42
Rail	Fish	Diesel	17.90	17.53	16.92	15.77	14.70
Rail	Fish	Electric train (CL)	0	0	0	0	0
Rail	Fish	Hybrid	12.53	12.01	11.20	9.73	8.45
Rail	Fish	Battery train	0	0	0	0	0
Rail	Fish	Hydrogen	0	0	0	0	0
Rail	Fish	Biodiesel	3.58	3.43	3.20	2.78	2.42
Rail	Thermo	Diesel	17.90	17.53	16.92	15.77	14.70
Rail	Thermo	Electric train (CL)	0	0	0	0	0
Rail	Thermo	Hybrid	12.53	12.01	11.20	9.73	8.45
Rail	Thermo	Battery train	0	0	0	0	0
Rail	Thermo	Hydrogen	0	0	0	0	0
Rail	Thermo	Biodiesel	3.58	3.43	3.20	2.78	2.42
Rail	Industrial goods	Diesel	17.90	17.53	16.92	15.77	14.70
Rail	Industrial goods	Electric train (CL)	0	0	0	0	0
Rail	Industrial goods	Hybrid	12.53	12.01	11.20	9.73	8.45
Rail	Industrial goods	Battery train	0	0	0	0	0
Rail	Industrial goods	Hydrogen	0	0	0	0	0
Rail	Industrial goods	Biodiesel	3.58	3.43	3.20	2.78	2.42
Rail	Timber	Diesel	30.80	30.16	29.12	27.14	25.30
Rail	Timber	Electric train (CL)	0	0	0	0	0
Rail	Timber	Hybrid	21.56	20.67	19.27	16.74	14.55
Rail	Timber	Battery train	0	0	0	0	0
Rail	Timber	Hydrogen	0	0	0	0	0
Rail	Timber	Biodiesel	9.24	8.86	8.26	7.18	6.23
Rail	Wet bulk	Diesel	25.50	24.97	24.11	22.47	20.95
Rail	Wet bulk	Electric train (CL)	0	0	0	0	0
Rail	Wet bulk	Hybrid	17.85	17.11	15.95	13.86	12.04
Rail	Wet bulk	Battery train	0	0	0	0	0
Rail	Wet bulk	Hydrogen	0	0	0	0	0
Rail	Wet bulk	Biodiesel	5.10	4.89	4.56	3.96	3.44

E Maturity Limits

Table 6: The maturity limits for all combinations of mode and fuel for all time periods and scenarios. L = low maturity, M = medium maturity, H = high maturity. The maturities are in percentage of the fleet for the associated mode.

Scenario	**Mode**	**Fuel**	**2022**	**2025**	**2030**	**2040**	**2050**
L	Road	Diesel	100 %	100 %	100 %	100 %	100 %
L	Road	Electricity	0 %	2 %	5 %	12 %	20 %
L	Road	Hydrogen	0 %	0 %	0 %	1 %	2 %
L	Road	Biodiesel	5 %	6 %	7 %	9 %	10 %
L	Road	Biogas	0 %	1 %	2 %	4 %	5 %
L	Sea	HFO	100 %	100 %	100 %	100 %	100 %
L	Sea	MGO	100 %	100 %	100 %	100 %	100 %
L	Sea	LNG	22 %	25 %	35 %	42 %	50 %
L	Sea	Hydrogen	0 %	0 %	0 %	0 %	0 %
L	Sea	Ammonia	0 %	0 %	3 %	6 %	10 %
L	Sea	Biodiesel	0 %	0 %	2 %	4 %	5 %
L	Sea	Biogas	0 %	0 %	2 %	4 %	5 %
L	Rail	Diesel	100 %	100 %	100 %	100 %	100 %
L	Rail	Electric train	100 %	100 %	100 %	100 %	100 %
L	Rail	Battery train	0 %	0 %	2 %	5 %	10 %
L	Rail	Hydrogen	0 %	0 %	0 %	0 %	0 %
L	Rail	Biodiesel	0 %	0 %	0 %	0 %	0 %
M	Road	Diesel	100 %	100 %	100 %	100 %	100 %
M	Road	Electricity	0 %	2 %	10 %	25 %	50 %
M	Road	Hydrogen	0 %	0 %	5 %	15 %	25 %
M	Road	Biodiesel	5 %	6 %	10 %	15 %	20 %
M	Road	Biogas	0 %	1 %	4 %	7 %	10 %
M	Sea	HFO	100 %	100 %	100 %	100 %	100 %
M	Sea	MGO	100 %	100 %	100 %	100 %	100 %
M	Sea	LNG	22 %	25 %	35 %	50 %	70 %
M	Sea	Hydrogen	0 %	0 %	2 %	6 %	10 %
M	Sea	Ammonia	0 %	0 %	3 %	12 %	25 %
M	Sea	Biodiesel	0 %	0 %	2 %	6 %	10 %
M	Sea	Biogas	0 %	0 %	2 %	6 %	10 %
M	Rail	Diesel	100 %	100 %	100 %	100 %	100 %
M	Rail	Electric train	100 %	100 %	100 %	100 %	100 %
M	Rail	Battery train	0 %	0 %	10 %	15 %	20 %
M	Rail	Hydrogen	0 %	0 %	1 %	3 %	5 %
M	Rail	Biodiesel	0 %	0 %	2 %	6 %	10 %
H	Road	Diesel	100 %	100 %	100 %	100 %	100 %
H	Road	Electricity	0 %	2 %	15 %	45 %	80 %
H	Road	Hydrogen	0 %	0 %	10 %	25 %	50 %
H	Road	Biodiesel	5 %	6 %	10 %	20 %	30 %
H	Road	Biogas	0 %	1 %	5 %	10 %	20 %

Scenario	**Mode**	**Fuel**	**2022**	**2025**	**2030**	**2040**	**2050**
H	Sea	HFO	100 %	100 %	100 %	100 %	100 %
H	Sea	MGO	100 %	100 %	100 %	100 %	100 %
H	Sea	LNG	22 %	25 %	40 %	70 %	100 %
H	Sea	Hydrogen	0 %	0 %	5 %	12 %	30 %
H	Sea	Ammonia	0 %	0 %	7 %	30 %	50 %
H	Sea	Biodiesel	0 %	0 %	5 %	10 %	20 %
H	Sea	Biogas	0 %	0 %	5 %	10 %	20 %
H	Rail	Diesel	100 %	100 %	100 %	100 %	100 %
H	Rail	Electric train	100 %	100 %	100 %	100 %	100 %
H	Rail	Battery train	0 %	0 %	10 %	30 %	50 %
H	Rail	Hydrogen	0 %	0 %	2 %	6 %	10 %
H	Rail	Biodiesel	0 %	0 %	5 %	10 %	20 %

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