Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Helle Johnsgård Jensen

The domestic bulk fleet's zero-emission potential based on hydrogen infrastructure development

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
Co-supervisor: Eivind Dale
June 2021

NTNU
Norwegian University of Science and Technology

DNV

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NTNU
Det skapende universitet

Master Thesis in Marine Systems Design

Stud. techn. Helle Johnsgård Jensen

"The domestic bulk fleet's zero-emission potential based on hydrogen infrastructure development"

Spring 2021

Background
Felleskjøpet and HeidelbergCement have opposite trades of grain and gravel between the Stavanger area and the Oslo fjord. Together with DNV they have established a tender with the objective to establish a sustainable transport system. The tender specifies one ship in weekly roundtrips combining these two trades and with zero emission of greenhouse gases during its operation. A new vessel is planned to be in operation by 2023. To reach the Norwegian governments target of 50% reduction of CO2 emission by 2030, a larger renewal of the fleet is necessary. In order for this to be possible the fleet is depending on a sufficient infrastructure.

Overall aim and focus
The overall aim of the project is to perform a scenario-based impact assessment of the domestic bulk fleet in Norway. Different scenarios for infrastructure development shall be developed. An impact analysis will be performed to see the emission reduction each scenario leads to. The result should be compared with the possibility to reach the Norwegian governments goal of a 50% reduction in emission by 2030.

Scope and main activities
The thesis should presumably cover the following main points:

1. A brief presentation of hydrogen and hydrogen infrastructure as well as the domestic bulk fleet in Norway.
2. Relevant literature study on scenario analysis and impact assessment.
3. Development of future scenarios for hydrogen infrastructure
4. Development of a quantitative model.
5. Performance of impact assessment using developed scenarios.
6. Analysis and discussion of results.
7. Validation of method.
8. Conclusion with recommendation for future work

Modus operandi
At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.
In addition, Eivind Dale will be the responsible advisor from DNV.
The work shall follow the guidelines given by NTNU for the MSc Master Thesis work

Stein Ove Erikstad
Professor/Responsible Advisor

Preface

This master thesis is written in the spring of 2021 as a part of my master's degree at the Department of Marine Technology, NTNU - Norwegian University of Science and Technology. The thesis corresponds to 30 ECTs.

The main objective of the thesis is to see how the development of infrastructure for compressed hydrogen affects the emissions from the domestic bulk fleet in Norway. During my study, I developed an interest in decarbonisation of the maritime industry. I wanted to write a thesis related to this. The objective is developed by me in collaboration with my supervisors. The theme is based on my project thesis from the autumn 2020 "Fleet renewal towards zero-emission for shortsea bulk shipping in Norway". Large parts of chapter 3 are taken from this project thesis.

This thesis has been written in collaboration with DNV. I would like to thank DNV for this opportunity. Working with this thesis has been very interesting and educational. It has increased my interest in the maritime industry and all the opportunities that lay here. I have achieved a broader view of the challenges related to decarbonisation together with an understanding of the importance of working towards a more sustainable industry.

I would like to thank my two supervisors Stein Ove Erikstad from the Department of Marine Technology and Eivind Dale from DNV for all guidance and valuable discussions throughout the last two semesters. I would also like to thank Arild Hoff from Egil Ulvan shipping company, Hans Kristan Haram from Flowchange and Eirik Overum from DNV for taking the time to participate in valuable and educational discussions regarding the future of domestic shipping in Norway.

Trondheim, June 10^{th} 2021

Helle J. Jensen

Helle Johnsgård Jensen

Sammendrag

Innenriksflåten i Norge har en gjennomsnittsalder på 28 år og er derfor moden for en utskiftning. Norske myndigheter har satt et ambisiøst mål om å redusere utslippet fra den norske flåten med 50% innen 2030. For å nå dette målet må flere lav- og nullutslippsskip være i drift innen 2030. Hvis dette skal være mulig er man avhengig av en tilfredsstillende utbygging av infrastruktur som kan levere nødvendig mengde drivstoff.

Denne masteroppgaven ser på hvordan utviklingen av infrastruktur for komprimert hydrogen i Norge påvirker innenriks bulkflåten sitt mulige reduksjon i utslipp. En kvantitativ modell bestående av ulike betingelser som definerer om en tur kan ble gjennomført ved bruk av hydrogen eller ikke har blitt utviklet. Drivstofftilgjengeligheten er modellert som et sett av lokasjoner med et tilgjengelig volum på hver lokasjon. Tre ulike scenarioer er utviklet. Base case scenarioet representerer den mest sannsynlige utviklingen basert på den kunnskapen man har i dag. I tillegg er det utviklet et mer optimistisk og et mer pessimistisk scenario. Drivstofftilgjengelighet i form av lokasjoner og volum samt mulige betingelser for et hydrogenbasert seilas endres mellom hvert scenario. Sammen gir resultatet fra de tre scenarioene god innsikt til hvordan utviklingen av infrastruktur for komprimert hydrogen i Norge påvirker mulig utslippsreduksjon i flåteutvalget.

Grunnet kompleksiteten til problemet måtte noen forenklinger gjøres når den kvantitative modellen ble utviklet. Disse forenklingene gir en feilmargin i resultatet som er oppgitt. Det er også usikkerhet knyttet til inputverdiene da disse antar en gitt utvikling i fremtiden. Ettersom det er brukt tre ulike scenarioer burde likevel ikke den overordnede konklusjonen ha et signifikant avvik.

Resultatet oppnådd i denne oppgaven viser at utbygging av infrastruktur sannsynligvis ikke er flaskehalsen for å oppnå en utslippsreduksjon for flåtesegmentet analysert. Basert på eksisterende planer for utvikling av produksjonskapasiteten til hydrogen, er det sannsynlig at nok hydrogen vil bli produsert, og at distribusjonen er god nok til å oppnå en utslippsreduksjon på 50% innen 2030 for alle scenarioene. Resultatet fra oppgaven tyder på at det er tilstrekkelig realisering og fornyelse av kyst- og nærskipsflåten som vil være hovedutfordringen med å nå de nasjonale målsettingene for 2030.

Summary

The domestic bulk fleet in Norway has an average age of 28 years and is in need of a replacement. The Norwegian government has defined an ambitious goal aiming for a 50% reduction of emissions from the domestic fleet by 2030. To reach this goal several low- and zero-emission vessels must be in operation by 2030. If several vessels running on low- and zero-emission fuels are to be in operation, there must be an adequate infrastructure.

This thesis looks at how the development of infrastructure for compressed hydrogen will affect the potential reduction in emissions for the domestic bulk fleet in Norway. A quantitative model is developed where different conditions define whether a voyage can be performed using hydrogen or not based on fuel availability. Fuel availability is modelled as a set of locations and an available volume at each location. Three different scenarios for hydrogen availability are developed. One base case scenario representing the most likely development, and two additional scenarios representing a more pessimistic and optimistic view. Fuel availability locations, volume, and refuelling conditions are changed between the three scenarios. Combined, the result from the three scenarios give a good insight into how the infrastructure development affects the potential emission reduction for the selected fleet.

Due to problem complexity, some simplifications had to be made during the development of the quantitative model. The simplifications will lead to some margin of error in the results. In addition, there are some uncertainties to the input values used as they are assuming a future development. However, since three scenarios are used, the overall conclusion of the thesis should not have a significant margin of error.

The result achieved in this thesis shows that infrastructure development will probably not be the bottleneck for emission reduction in the fleet selection analysed. Based on existing plans for the development of hydrogen production capacity, it is likely that enough hydrogen will be produced, and the distribution of availability locations is sufficient to reach a 50% reduction in emissions by 2030 for all scenarios analysed. The result indicates that it is a sufficient renewal of the domestic fleet that will be the main challenge in reaching the national emission goal for 2030.

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Acronyms

CCS Carbon Capture and Storage. 8–10, 12, 16, 53

EIA Environmental Impact Assessment. 22

FC Fuel Cell. 9, 14, 15

GHG Greenhouse Gas. vii, 2, 7, 8

GSP Green Shipping Programme. viii, 31, 40–42, B

IA Impact Assessment. v, viii, 2, 5, 20, 22, 24, 45, 47, 48, 54

ICE Internal Combustion Engine. 14, 15

LCA Life Cycle Assessment. 22, 23

LCC Life Cycle Cost. 12

LCE Life Cycle Emission. vii, 4, 8, 12, 53

LOHC Liquid Organic Hydrogen Carriers. 8, 16

PEM Proton Electrolyte Membrane. 9, 17

SMR Steam Methane Reforming. 8, 9, 12, 53

SOFC Solid Oxide Fuel Cell. 9

1. Introduction

Transportation stands for almost 60% of the Norwegian non-quota emissions (Meld. St. 41 2016 - 2017). The transportation sector includes, among others, shipping and fishery which in 2019 stood for 2.98 million ton CO_2 - equivalents, compared to road transport which is the largest contributor in the Norwegian transport sector and stands for 8.5 million ton CO_2 - equivalents (Miljødirektoratet 2020). From 1990-2019 the Greenhouse Gas (GHG) emissions in Norway were reduced by 2.3%. Emissions from road transport decreased by 7.3% from 2018-2019. Emissions from the "other transport" sector decreased by 4.5% from 2018-2019. In 2019, shipping and fishery stood for about 43% of the "other transport" emission category (Statistisk sentralbyrå 2020). The Norwegian Environment Agency connects the reduction in emissions to the activity change, streamlining, and electrification in this sector. Further, they connect the reduction in GHG emissions from shipping and fishery, to the reduction in offshore activity, technology development, and transformation to less emission intense fuels (Miljødirektoratet 2020).

Felleskjøpet and HeidelbergCement have opposite trades of grain and gravel between the Stavanger area and the Oslo fjord. In collaboration, they have established a tender with the objective to establish a more sustainable transport system. One zero-emission vessel shall in weekly round trip combine these two trades. Egil Ulvan shipping company won the tender, and a new vessel is planned to be in operation by 2023. The Norwegian government has an ambitious goal to reduce the CO_2 emissions from domestic shipping by 50% by 2030 (Nærings- og fiskeridepartementet 2020). To reach this goal, 700 low-emission and 400 zero-emission vessels must be in operation by 2030 (Grønt Skipsfartsprogram n.d.). For this to be possible, a corresponding infrastructure for low- and zero-emission fuels must be developed. The Norwegian government writes in their climate strategy for 2030 (Meld. St. 41 2016 - 2017, page 71) that the development of a sufficient infrastructure for alternative fuels is a prerequisite for zero- or low-emission fuels to be used on a larger scale.

This thesis will perform a scenario-based Impact Assessment (IA) of how the infrastructure development for compromised hydrogen affects the domestic bulk fleet's zero-emission potential. A quantitative model has been developed to calculate the emission changes based on different scenarios for hydrogen availability. The scenarios are based on ongoing and upcoming hydrogen projects and assumed price developments for hydrogen.

In short terms, the thesis includes the steps from the work process shown in figure 1.

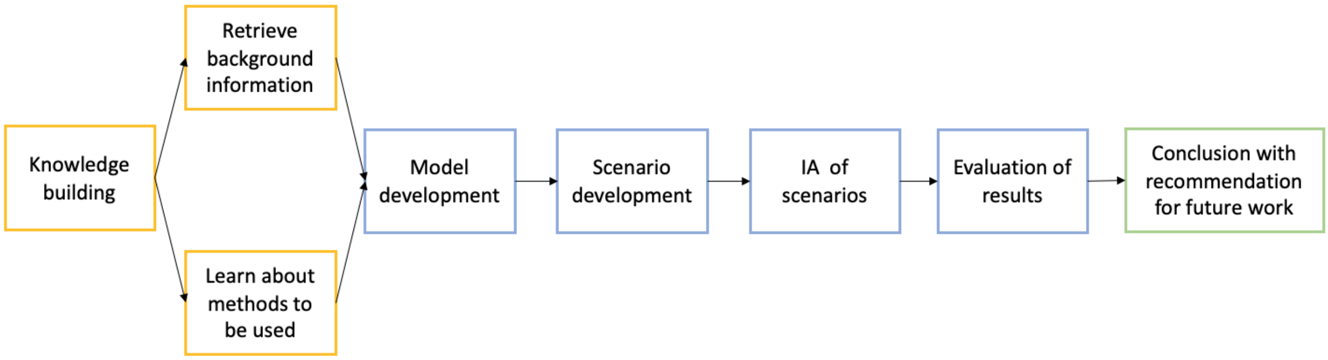


Figure 1.: Work process of thesis.

The first chapter in this thesis describes how the system boundaries were established. The next chapter provides a background study on hydrogen as an energy carrier and the domestic bulk fleet in Norway. This knowledge is necessary for developing a quantitative model later in the thesis. Chapter 4 describes the method used by introducing impact assessment and scenario analysis.

Chapter 5 and 6 is the beginning of the main part of the thesis describing the model development. Chapter 5 gives a mathematical description of the output and restrictions. Chapter 6 describes how the mathematical functions are implemented to a calculation model using Python. Chapter 7 describes how the different scenarios are developed. The next chapter describes the results followed by an evaluation of the model. Lastly, there is a conclusion with recommendation for future work.

2. Establishing system boundaries

There is an increased interest in hydrogen in domestic shipping. This thesis will therefore look at the zero-emission potential for the domestic bulk fleet in Norway based on assumed availability development for compressed hydrogen.

Reducing emissions from shipping is more than reducing emissions directly from the vessel. Figure 2 illustrates the Life Cycle Emission (LCE) for hydrogen fuel used in a vessel. Each of the nodes in the value chain affects each other, and each node can be decomposed into several sub-nodes. If the distances from the production facilities to the port is large, the transport emissions will increase. In addition, the transportation emissions will also depend on the number of production facilities and the number of ports.

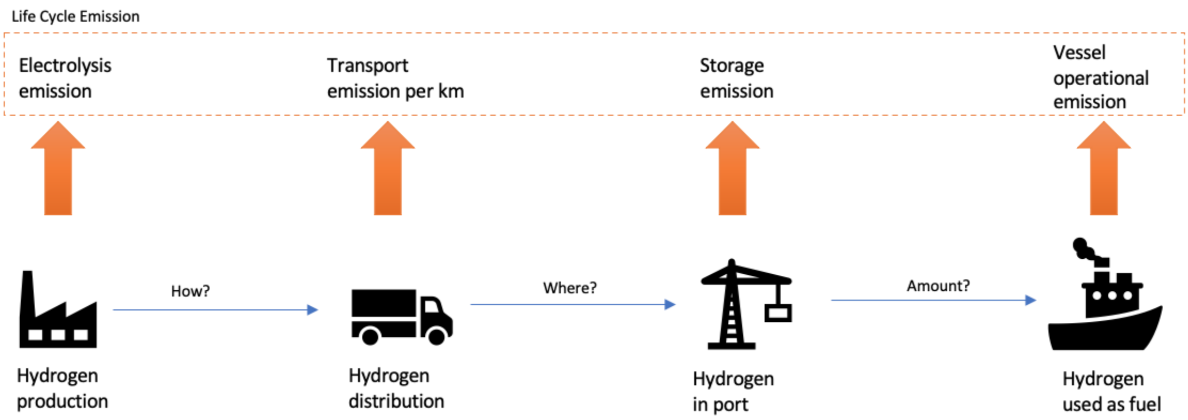


Figure 2.: Illustration of LCE for hydrogen as maritime fuel

There are multiple ways to reduce emissions from shipping, leading to multiple ways to formulate a problem statement.

The problem can be formulated as an optimisation problem saying that a given amount of the fleet should run on hydrogen, and then optimise the locations of the ports to minimise costs.

Another angle is to say that the location and number of ports with hydrogen available are defined. Then you can optimise the fleet's operational pattern in order to reduce emissions based on the locations of the ports.

The existing operational pattern of the domestic bulk fleet in Norway can be retrieved from AIS data. These data do not include cargo flow data. There is no easy way to get information about the cargo flow data for the entire fleet except retrieving the data from cargo owners, shipping companies in combination with port statistics. To optimise the fleet operational pattern, knowledge of cargo flow is needed. Therefore, due to too many uncertainties, it was for this thesis not relevant to perform an optimisation of the fleet's operational pattern.

One could optimise the location of production facilities based on ports with fuel available. However, the hydrogen infrastructure in Norway will depend on many factors besides just the domestic bulk fleet. Therefore, the location of production facilities will depend on hydrogen demand from all industries in Norway. This demand will again depend on technology development and assumptions on future developments in the energy sector. Again, there are too many unknowns for optimisation being a good solution method at this stage.

What is known is the existing operational pattern and the existing ports. With this knowledge, one can perform an IA looking at how hydrogen availability in the existing ports affects the existing fleet's zero-emission potential using today's operational pattern. Based on known development today, and assumed development reaching 2030, different scenarios for hydrogen availability can be created. This will give insight into the assumed emission reduction based on each scenario, and how each scenario performs compared to the emission goals set by the Norwegian government.

The model in this thesis will therefore have the system boundaries, input, and output as illustrated in figure 3.

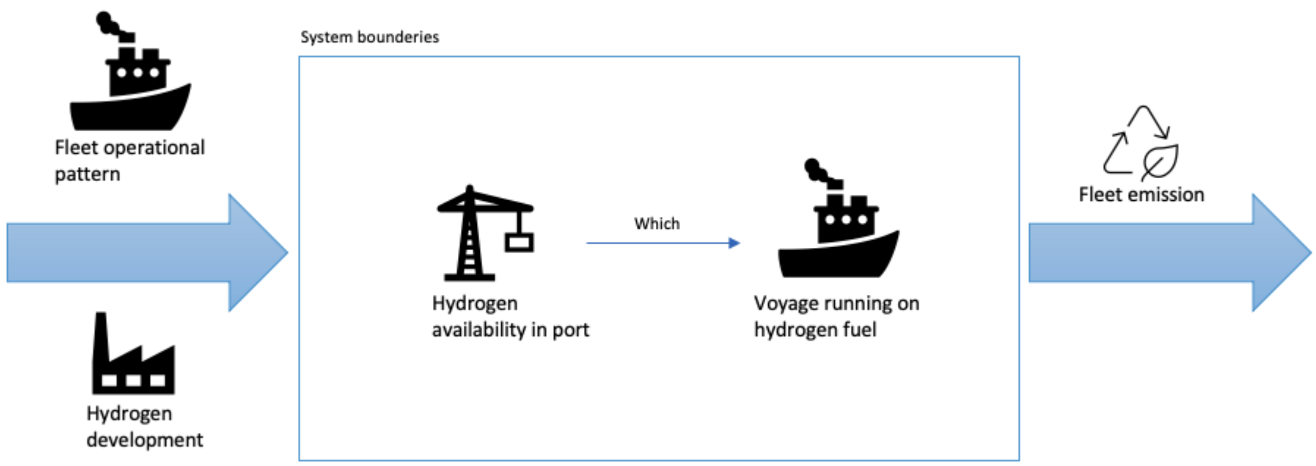


Figure 3.: Illustration of system boundaries for thesis

This thesis will use the existing operational pattern of a selected part of the domestic bulk fleet. The fleet selected consists of 146 vessels. It is defined that the vessels included must operate at least 15% of their time in Norway. The average size of the vessels in the selection is 3300 dwt. However, the size varies between 1500 - 25 000 dwt. The desired output of the analysis is to see how infrastructure developments will affect the fleet's ability to reach the Norwegian government's emission goal. Therefore, only voyages from one Norwegian port to another is used. Further in this thesis, this fleet selection will be referred to as "the domestic bulk fleet".

3. Background study

The following sections will give background information to emission reduction in shipping, hydrogen as an energy carrier, and the existing domestic bulk fleet in Norway. This should give the necessary knowledge to develop a quantitative calculation model and create hydrogen availability scenarios later in the thesis.

3.1. Emission reduction in shipping

There are mainly two ways to reduce GHG emissions. One can either reduce energy consumption or change energy source. Figure 4 gives different solutions for both related to a vessel. The figure shows that the only way to have a 100% reduction of GHG emissions on a vessel is by changing to a zero-emission fuel such as hydrogen or other synthetic fuels.

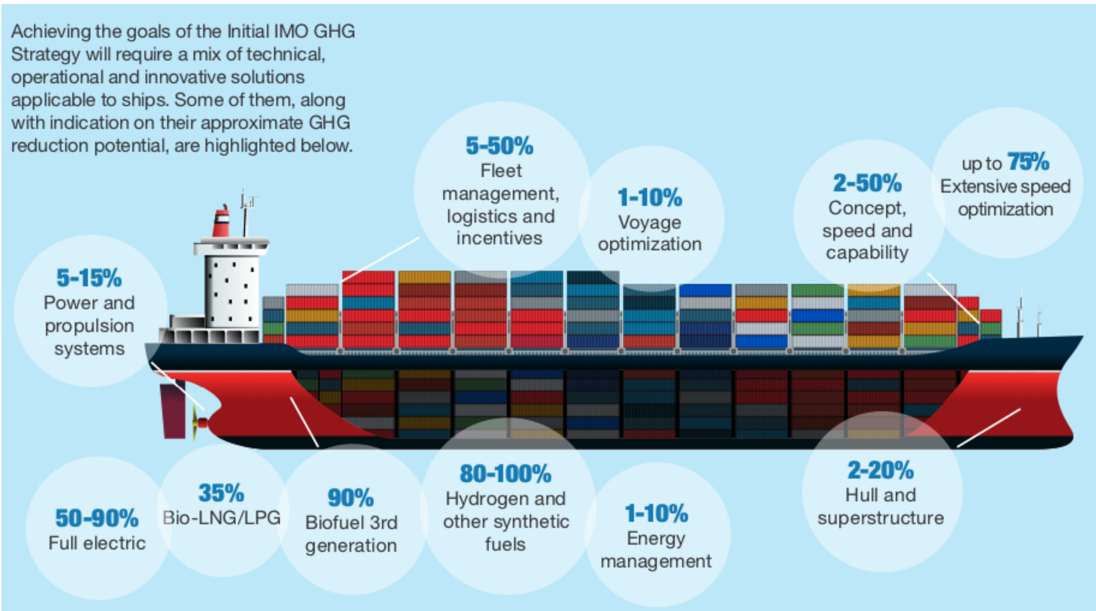


Figure 4.: Excerpt from IMO's action to reduce GHG emissions from international shipping brochure giving different GHG emission reduction potentials. (IMO n.d.)

There is a wide range of choices for zero- and low-emission fuels for maritime application. Today, none of these points out to be the best solution. However, some are more applicable for shortsea than deepsea shipping.

Batteries have low volumetric and gravimetric energy density as shown in figure 8. As the energy storage demand increases with increasing range demand, batteries become less applicable as they take up too much space and tonnage capacity. However, for shortsea with low range demand, fully electric propulsion systems with batteries can be suitable.

Hydrogen has a low volumetric energy density and will therefore demand a significant amount of space as the range demand increases. A solution to the storage problem of hydrogen is to store hydrogen in another substance with higher volumetric energy density, such as ammonia, Liquid Organic Hydrogen Carriers (LOHC), or methanol. A challenge using hydrogen carriers is increased energy loss in the fuel production chain.

In 2020, the Norwegian government released a hydrogen strategy (Norwegian Ministry of Petroleum and Energy Norwegian Ministry of Climate and Environment 2020). This strategy describes hydrogen as an exciting opportunity for Norway as an energy and technology nation. The conditions in Norway are ideal due to high experience across the entire hydrogen value chain, combined with ideal geographical locations that have good potential for both Carbon Capture and Storage (CCS) and renewable energy. Due to the increased interest in hydrogen in multiple sectors today, hydrogen is one of the most promising zero-emission fuels in domestic shipping.

3.2. Hydrogen as an energy carrier

Hydrogen is not an energy source, but an energy carrier. It is the simplest element on earth consisting of only one electron and one proton. Hydrogen atoms do not exist in nature alone and must therefore be separated from other elements where it occurs.

This section will provide information on hydrogen and how its characteristics affect infrastructure developments and demands.

3.2.1. Production

There are several ways to produce hydrogen. Each production method has different advantages and disadvantages. Common for all is that to reduce the LCE of a hydrogen-fuelled vessel, green production is desired. Hydrogen has no GHG emissions in operation, but the production emissions highly depend on the production method. There are mainly three pathways to hydrogen: biomass, natural gas, and electricity see figure 5.

As the figure illustrates, both natural gas and biomass can produce hydrogen through a reforming process. Most common today is Steam Methane Reforming (SMR). About 95% of today's hydrogen production stems from fossil fuels (U.S. Department of Energy n.d.). The SMR method has a carbon footprint today of about 10–12 kg CO2-eq per kg hydrogen produced (Aarnes, Haugom, and Norheim 2019). This corresponds to about 330 g-eq/kWh. These emissions can be reduced by using CCS.

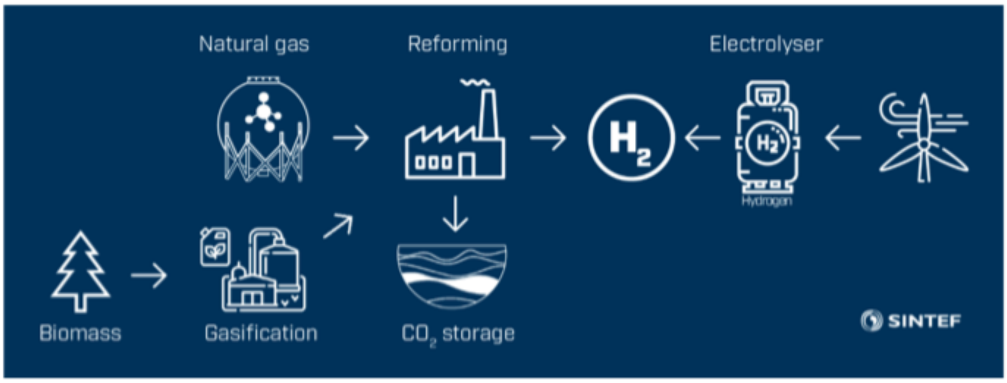


Figure 5.: Hydrogen production pathways (Reigstad et al. 2019, page 7)

Another production pathway for hydrogen is electrolysis. The emissions from this process are highly dependent on the energy mix used. Electrolysis separates hydrogen and oxygen in water using electrical power. There are two main methods in use today, Proton Electrolyte Membrane (PEM) and alkaline electrolysis. Another method is also under development: Solid Oxide Fuel Cell (SOFC), however, this method is still in a demonstration state. The advantage of the last two methods is that they can be used reversed as a Fuel Cell (FC) (Aarnes, Haugom, and Norheim 2019).

Sintef compares hydrogen production from natural gas using CCS, with electrolysis using the European energy mix in their study (Reigstad et al. 2019), see figure 6.

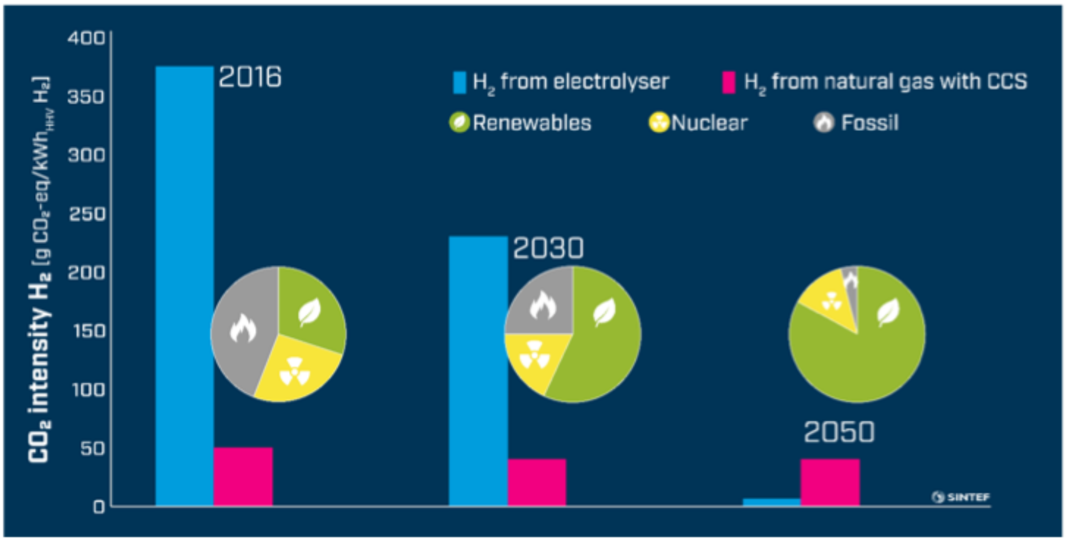


Figure 6.: Comparing emissions from hydrogen production using natural gas and electrolysis pathway. The piecharts illustrate the energy mix.

The figure shows that if hydrogen is produced using electrolysis and today's energy mix, the emissions are almost the same as SMR without CCS (330 g-eq/kWh). However, as the energy mix becomes greener, electrolysis has a better performance. With over 90% green energy, the emissions using electrolysis will be much lower than SMR with CCS. Based on the Sintef study, this is assumed to happen between 2030 and 2050.

Cost of hydrogen production

Depending on the production method, hydrogen can have significant variations in production cost. Figure 7 from IEA gives the cost range for hydrogen production by source. The figure shows that the most expensive production method is low-carbon electricity and that production cost using natural gas with CCS is quite low. However, it is assumed that in 2060 the production cost using low-carbon electricity will be significantly reduced, but still be more expensive than production using natural gas with CCS.

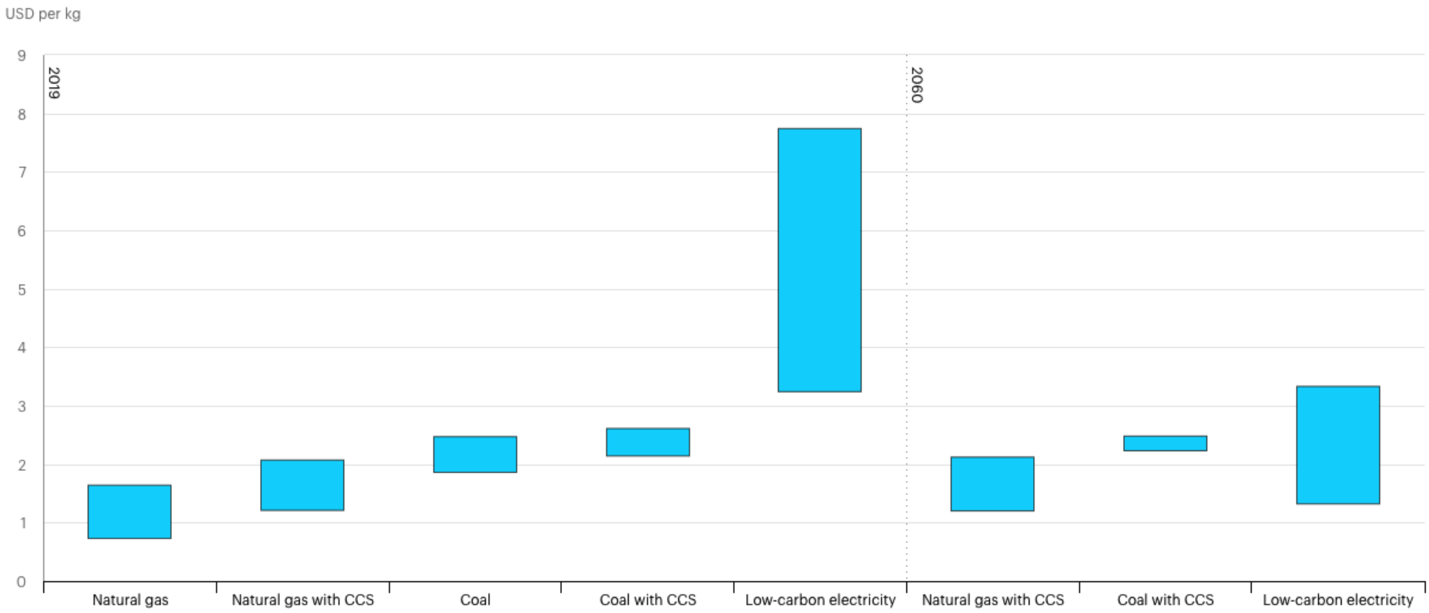


Figure 7.: Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050 (IEA 2020)

DNV writes in their report on hydrogen use in Norway that the production cost of hydrogen using PEM electrolysis will range between 30-50 NOK/kg hydrogen (Aarnes, Haugom, and Norheim 2019). Production using alkaline electrolysis will reduce the cost by around 8 NOK. The study assumes a small cost reduction reaching 2030. For hydrogen production using steam reforming and CCS, the DNV report assumes that the cost will range between 9-15 NOK/kg hydrogen.

3.2.2. Storage

There are several ways to store hydrogen depending on the purpose. Following are some alternatives:

- Pure form
- Liquid form

- Compressed gas, most commonly 350 or 700 bar.
- In a hydrogen carrier molecule such as ammonia or methanol

Hydrogen has low volumetric energy density compared to other commercial fuels as shown in figure 8 taken from a DNV article on hydrogen production in Norway (Aarnes, Eijgelaar, and Hektor 2018, page 46). However, the figure also shows that hydrogen has the highest gravimetric energy density compared to the other energy carriers.

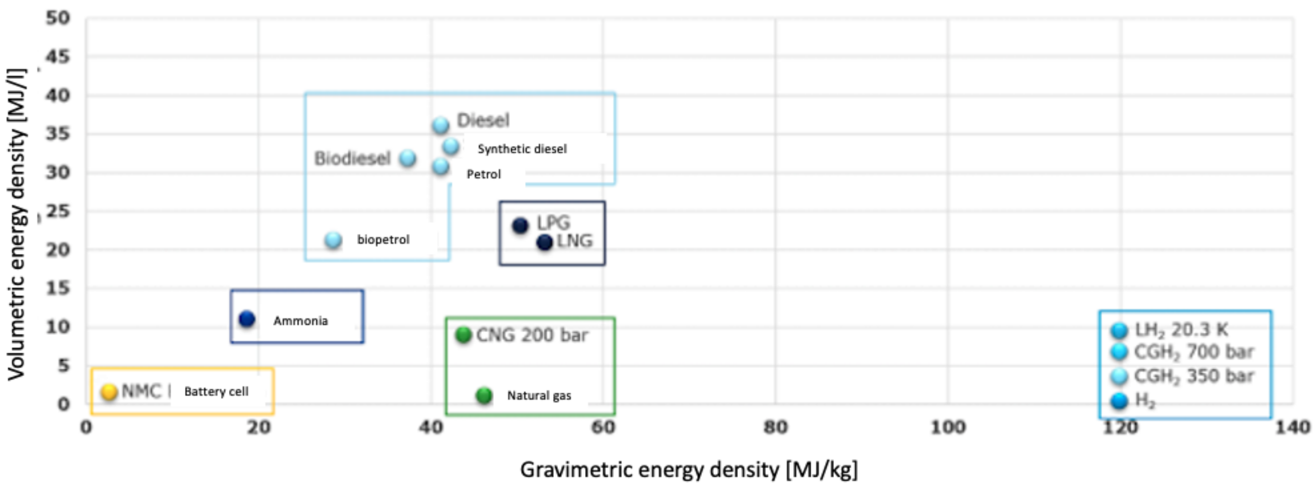


Figure 8.: Volumetric and gravimetric energy density for hydrogen and other energy carriers (Aarnes, Haugom, and Norheim 2019, page 46).

Ammonia has a slightly higher volumetric energy density compared to liquefied hydrogen. For hydrogen to be in liquid form it must be cooled down to 20ºK (-253ºC). This will demand about 20-30% of the original energy content of the hydrogen (Commonwealth of Australia 2018). Ammonia on the other hand is liquid below -33,4 ºC (Pedersen 2018) which demands significantly less energy in storage. In Norway today, there is little knowledge and no facilities for liquefying hydrogen. In Europe, there are only 3 facilities, and they have a production capacity of around 5-10 ton LH_2/day (Aarnes, Haugom, and Norheim 2019, page 32).

Compressed hydrogen stored at 30 bars will demand energy equal to 4-5% of the original energy content of the compressed hydrogen. Further compression to 350 or 700 bars will demand additional 4-8% of the original energy content (Aarnes, Haugom, and Norheim 2019).

Cost of hydrogen storage

Figure 9 from DNVs report on hydrogen in Norway (Aarnes, Haugom, and Norheim 2019) gives the cost of hydrogen storage per kg for a case with 1000 km vessel transport and 15 days of storage for three different storage methods. The case assumes 400 MW hydrogen production capacity using gas reforming for a facility producing 100 000 tons hydrogen per year.

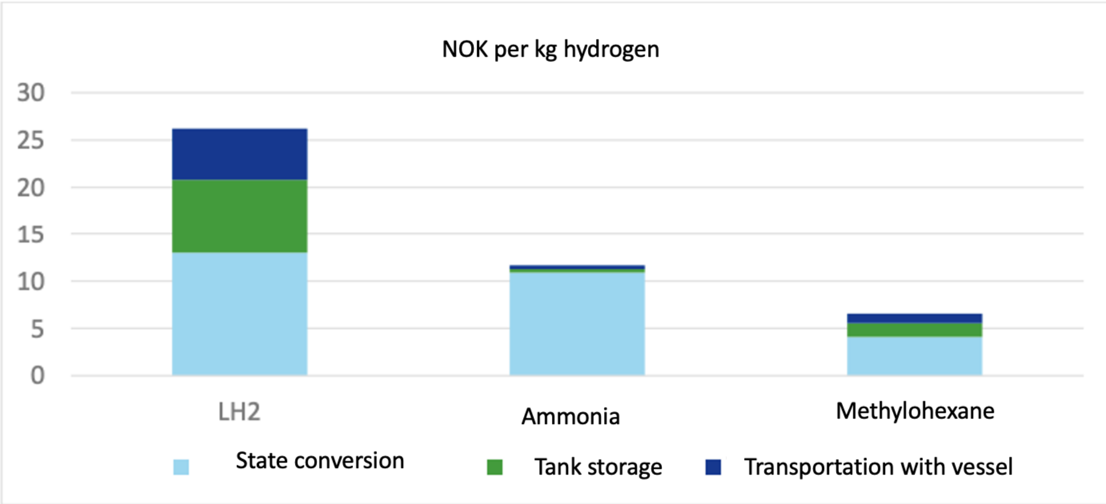


Figure 9.: Cost of hydrogen conversion, storage, and transportation (Aarnes, Haugom, and Norheim 2019, page 107)

Only looking at state conversion and tank storage, liquid hydrogen costs around 20 NOK per kg hydrogen, while ammonia costs about 10 NOK. The cost of state conversion is almost the same, but tank storage of liquid hydrogen is almost the same as for the state conversion, which leads to liquid hydrogen having twice as high costs compared to ammonia storage.

The figure from DNV's report does not include compressed hydrogen. Lloyd's Register together with UMAS performed a techno-economical assessment for zero-emission fuels (Lloyd's Register and UMAS 2020). In this report, they assume a hydrogen production plant with a capacity for production of 500 000 ton/year. The research includes two hydrogen pathways, electrolysis, and SMR with CCS. For both pathways, the conversion process has a CAPEX of 0.965 $/kg and an operation cost of 3% of this CAPEX cost. The storage cost is assumed to have a CAPEX equal to 0.02 $/kWh and an operational cost equal to 3% of this CAPEX.

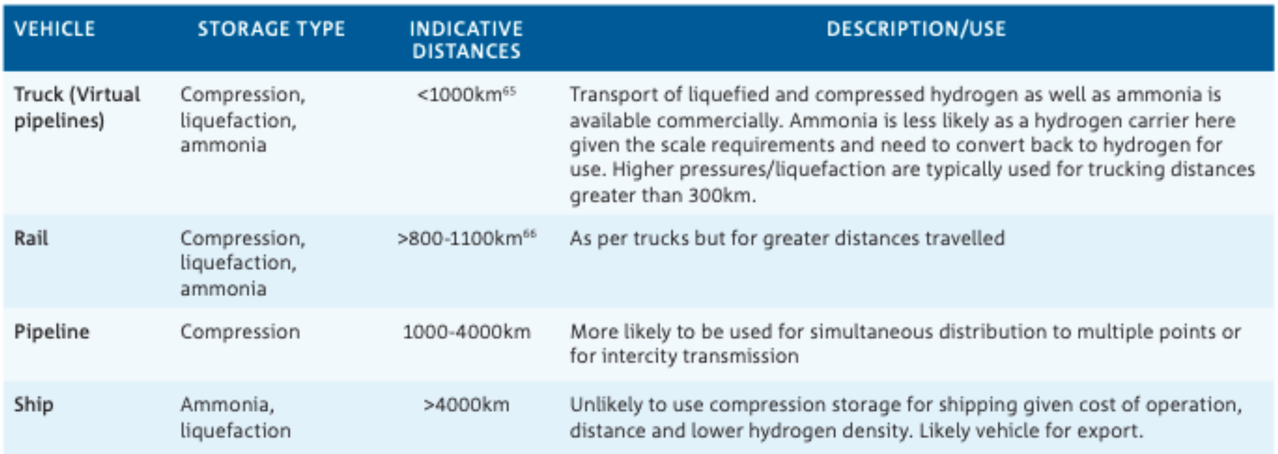
3.2.3. Transport

To have a well-functioning hydrogen infrastructure there must exist an efficient way to transport the hydrogen from the production site to the consumption site. This can be done with pipelines, rail, trucks, or vessels. Hydrogen can be transported in different forms. The best solution depends on the situation.

The distance and method for hydrogen transport will affect the LCE and LCC. If the goal is to reduce emissions in shipping using hydrogen fuel, the solution will depend on more than the vessel design. If the vessel has no operational emissions, but the hydrogen is produced in Australia and then transported on a vessel running on fossil fuel to Norway, the LCE might increase. In addition, increased transportation distance leads to increased LCC.

Infrastructure for hydrogen transport does exist today due to hydrogen use for industrial applications. However, it is not sufficient to support an up-scaling if hydrogen is to be used as an energy carrier.

For small volumes of hydrogen, transport using trucks can be sufficient. Then the energy density is important. Based on today's technology, liquid hydrogen might be more cost-efficient than compressed hydrogen, as increased energy density will make up for increased production cost and evaporation (Aarnes, Haugom, and Norheim 2019). For increased volume and transport over a longer distance (1000-4000 km) (CSIRO 2018), transport with pipelines is most likely the best solution. Today, about 4500 km of hydrogen pipelines exist, most of which are in the USA (Aarnes, Haugom, and Norheim 2019). Figure 10 from the CSIRO report gives an overview of the different transportation methods and when they are most applicable.



VEHICLE	STORAGE TYPE	INDICATIVE DISTANCES	DESCRIPTION/USE
Truck (Virtual pipelines)	Compression, liquefaction, ammonia	<1000km[65]	Transport of liquefied and compressed hydrogen as well as ammonia is available commercially. Ammonia is less likely as a hydrogen carrier here given the scale requirements and need to convert back to hydrogen for use. Higher pressures/liquefaction are typically used for trucking distances greater than 300km.
Rail	Compression, liquefaction, ammonia	>800-1100km[66]	As per trucks but for greater distances travelled
Pipeline	Compression	1000-4000km	More likely to be used for simultaneous distribution to multiple points or for intercity transmission
Ship	Ammonia, liquefaction	>4000km	Unlikely to use compression storage for shipping given cost of operation, distance and lower hydrogen density. Likely vehicle for export.

Figure 10.: Hydrogen transportation methods (CSIRO 2018, page 54)

Cost of hydrogen transport

Increased transport distance will increase the transport cost, which is an important part of the resulting fuel cost for hydrogen as illustrated in figure 9. Centralised production of large volumes will decrease the production cost, but it will also increase the transport distance. Local production will likely have higher production costs due to lower production volumes, but it will have lower or no transport distance. Figure 11, also from the (CSIRO 2018) report, gives the transport cost for different hydrogen forms using truck, rail, and vessel. The highest cost per ton-km is for trucks in all categories. However, this table does not account for the investment costs of each category. Trucks have the lowest investment cost which will make up for the increased transport cost for smaller volumes.

Pipeline is not included in the table in figure 11. Figure 12 gives the pipeline cost for three different materials with different maximum pressure.

METHOD	COMPRESSION ($/tkm H_2) 430 bar	LIQUIFICATION ($/tkm H_2)	AMMONIA ($/tkm NH_3)
Truck	2.33	0.92	0.33
Rail	0.55	0.28	0.04
Shipping	0.52	0.09[69]	0.03

Figure 11.: Transportation cost for hydrogen (CSIRO 2018, page 54)

	CONDITIONS[71]	MAX PRESSURE	SIZE (DIAMETER)	COST
		bar	mm	$/tkm
Steel	Transmission	103	200	0.82
FRP	Transmission	103	3 x 115	0.61
PE	Distribution	20	150	2.58

Figure 12.: Transportation cost for hydrogen transported in pipelines (CSIRO 2018, page 54)

3.2.4. Hydrogen as a maritime fuel

Refuelling options

There are two ways to refuel compressed hydrogen: cascade filling or container swap. A cascade filling system is based on pressure differences. If possible, fluids will flow in the direction where the pressure is lowest. With higher pressure on the hydrogen at quayside versus onboard, the hydrogen will flow to the onboard tanks. Compressed hydrogen can be stored and transported in container modules. This makes it possible to switch containers when refuelling instead of refuelling the onboard tanks. Due to the explosion hazard of hydrogen, both vessel and port will have regulations related to refuelling.

Energy conversion

There are mainly two energy conversion technologies relevant for hydrogen propulsion in maritime transport, these are FC and Internal Combustion Engine (ICE).

The challenge with using hydrogen as maritime fuel is safety. Due to this being a new fuel type, rules and regulations are not fully developed. DNV has developed rules for FC onboard ships. However, there are still gaps in regulations regarding hydrogen storage. The international code of safety for ships using gases or other low-flashpoint fuels (IGF code 2017) is an IMO code which means it is mandatory to follow for all gaseous and other low-flashpoint fuelled ships. The IGF code currently (2021) covers liquid natural gas and compressed natural gas. Regulations for other gases or low-flashpoint fuels are under development.

In a FC the hydrogen is converted into electrical energy that drives an electric motor. This gives flexibility for placement of engine components compared to a traditional ICE which produces mechanical energy. In an ICE, the shaft is driven by the main engine and must therefore be at the same level as the main engine. For an electrical system, the FC can be placed anywhere. Only the electric motor must be at the same level as the propeller. ICE may also be used as a electrical energy generator in an electrical system as described for FC. However, the overall power efficiency will be somewhat lower compared to FC. The FC will take up less space than an ICE releasing more space for cargo capacity or fuel storage.

The advantage with ICE is that ICE has a higher tolerance for fuel impurities. A possible fuel solution is, as mentioned in section 3.2.2, to use ammonia as a hydrogen carrier. In this case, ammonia must be cracked to fuel a hydrogen FC or ICE. Cracking might give an uncertainty for the purity of the hydrogen used. In addition, a hydrogen ICE is more like today's solution which will give a reduced cost by the opportunity to use existing manufacturing facilities. The ICE also allows a dual-fuel solution. This is especially convenient while there is limited infrastructure for hydrogen fuel.

3.2.5. Hydrogen infrastructure development

In 2019, 225 000 tons of hydrogen were produced in Norway (Horne and Hole 2019). The hydrogen was produced using natural gas, a process that has high CO_2 emission. In 2019 the cost of production using natural gas was 1/3 of the cost of producing hydrogen in a greener way.

Today most of the hydrogen produced is for industrial use. However, with an increased focus on decarbonisation of the energy- and transportation sectors the interest in hydrogen is increasing. Multiple hydrogen projects are developing nationally, and internationally. In 2020, the Norwegian government presented an increased focus on hydrogen in Norway. Later in 2020 they granted 38 million NOK to three project which shall give solutions for hydrogen use and production in Norway (Norwegian Government 2020). The three projects are:

- NEL Hydrogen Electrolyser AS which shall perform the last stage in the development of pressurised alkaline electrolyte. The goal is to deliver a cost-efficient large-scale hydrogen production that can handle fluctuations in production due to varying renewable energy production.
- Nexans AS, which in collaboration with Sintef, shall develop subsea energy transport for both electric power and hydrogen.
- Aker Solutions AS, which shall develop technology for production of hydrogen from natural gas relevant to the Norwegian focus on large-scale CO_2-management.

The map below in figure 13 is based on the hydrogen map at the Norwegian Hydrogen forum (Norsk hydrogen forum n.d.). The map gives locations for potential hydrogen production facilities and filling stations for hydrogen in a maritime application.

For the ferry connection Hjelmeland–Nesvik–Skipavik, Norled AS is building a hydrogen-electric ferry (Førde 2021). MF Hydra arrived in Norway in early 2021. The ferry will have two FCs in addition to a battery pack. Liquid hydrogen is used. Since this is not produced in Norway it will be transported by truck from Germany .

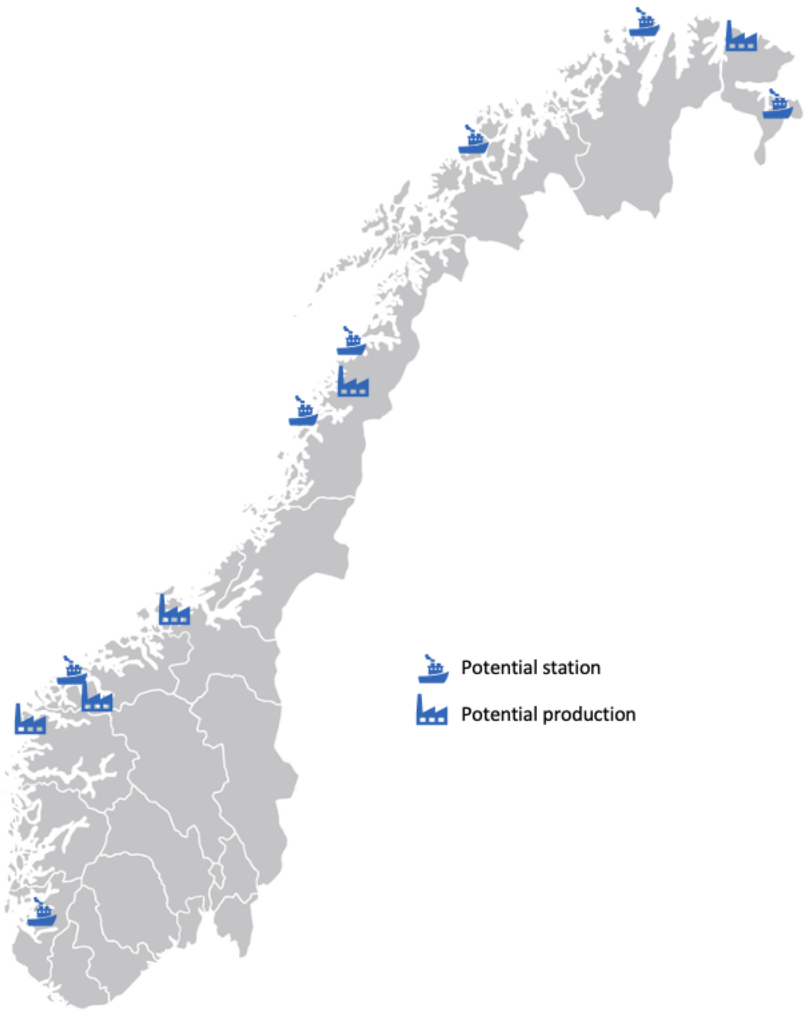


Figure 13.: Location of possible hydrogen production facilities and filling stations.

In 2020 INC Invest and Sogn og Fjordane Energi (SFE) formed Hyfuel (Stensvold 2020). Hyfuel was formed to establish a green hydrogen production facility in Florø. The production facility will focus on producing LOHC. The INC group owns the Fjord Base in Florø with 2000 port calls each year. LOHC is an alternative for green hydrogen-based fuel. Looking at figure 9 from DNV's report, LOHC is represented by methylcyclohexane and shows that LOHC is more profitable in transport than liquid hydrogen.

Hellesylt Hydrogen Hub is a project in the Geirangerfjord for a full hydrogen value chain with production, storage, and delivery of green hydrogen to ferries and cruise vessels in the Geirangerfjord (Stranda Kommune 2019).

In Tjeldbergodden, Equinor looked at producing hydrogen from gas. However, the project was paused and will not be worked further with without a solution for CCS (Viseth 2020).

The Northern Lights is a project for CO_2 storage on the Norwegian Continental Shelf (Northern Lights n.d.). The project is a collaboration between Equinor, Shell, and Total. By developing an infrastructure for transport of CO_2 from capture cites to permanent storage on the Norwegian Continental Shelf, the project has a storage capacity, and with that a CO_2 reduction potential of 1.5 million ton of CO_2 each year.

In 2020, Glomfjord Hydrogen signed a letter of intent with Air Liquide with an ambition to create a hydrogen infrastructure for production and liquefication of green hydrogen using electrolysis in Glomfjord industry park (Greenstat 2020). The goal is to provide zero-emission fuels for new ferries in the area. The project is also looking at the possibility for an upscaling to provide hydrogen for other marine applications, land transport, or industry purposes.

In Finnmark, the EU Haeolus project is located. The project uses PEM-based electrolyser to produce hydrogen from wind power (Stensvold 2018). The electrolyser has an effect of 2.5 MW with a production capacity of 1 ton hydrogen per day. The project is currently in a pilot state to see if the technology works. Varanger Kraft has a concession for developing 200 MW of wind power. Today only 45 MW have been built due to exportation limitations. By producing hydrogen, surplus energy can be exported or stored and used in local industry.

3.3. The Norwegian bulk fleet

Domestic bulk transportation in Norway has up until now to a small extent been mapped. In 2018, DNV performed a case-based study mapping the domestic dry bulk shipping market in Norway (Dale 2018). The study aimed to contribute to increased knowledge of the shortsea bulk market in Norway to give input to the domestic shipping strategy.

DNV performed a further development of the study which was published in January 2020 (Dale 2020). This study aimed to increase the knowledge base of the shortsea bulk market in Norway by analysing transportation and volume patterns of the most important goods. Some of the discoveries of this study will now be presented.

The study is based on 146 ships with an average size of 3300 dwt which operate 15% or more of their time in Norwegian waters.

The study found that the average age of today's fleet is 28 years. There are very few ships built after 2010, and the newest ships are among the largest in the fleet.

58% of the goods transported by the fleet are raw construction materials. Industrial minerals and metallic ores are the second largest group and stand for 21% of the transported goods. The third largest group is forestry and agriculture, which stands for 9% of transported goods. Contract cargo with an agreement of 3-5 years and spot cargo are the most common form of contract.

The average time in ballast conditions varies between 15-40%.

Ships travel to a small extent in shuttle between two ports. With about 1200 port calls it is hard to define a pattern other than that the port structure today is highly decentralised. The ships use, to a large extent, industry quays and quays that are not registered as ports. These quays are often small and not available for the larger ships in the fleet. It is expected that the demand for small volume transport to small quays will continue in the years to come.

The shipowners are positive and expect an increase in the demand for goods transport over the next years. With an old fleet, there will be a need for a fleet renewal to meet this increase. Further, the report says that the overall challenge with a fleet renewal is financing. The freight rates are too low and there are few long-term contracts that can provide financial security when taking up a loan. As of today, the owners of the goods are not willing to pay for more sustainable transport. The result is that with the current situation the shipowners cannot afford a fleet renewal.

There is too high financial risk associated with investing in smaller ships (750-2000 dwt). The shipowners are therefore more likely to invest in larger ships, typically between 3500-6500 dwt.

AIS data is used to perform a mapping of the operational pattern for the current fleet. Figure 14 gives the result for domestic transport. The figure shows that goods are transported along the entire Norwegian coast, but the density increases further south.

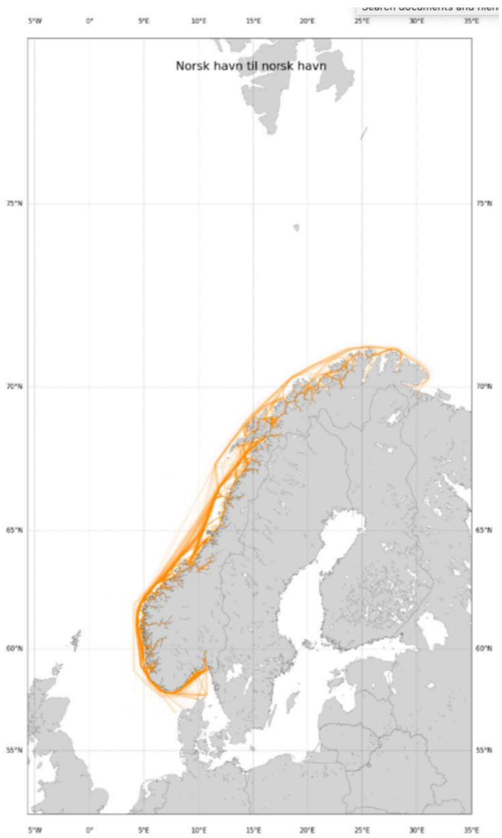


Figure 14.: Density plot of vessels sailing from a Norwegian port to another Norwegian port (Dale 2020, page 25)

Figure 15 shows that the average sailing distance between Norwegian shores increases with increased ship size.

The Norwegian government's climate strategy for 2030 (Meld. St. 41 2016 - 2017, page 66) describes the government's desire to move more goods transportation from the road to sea or rail. This

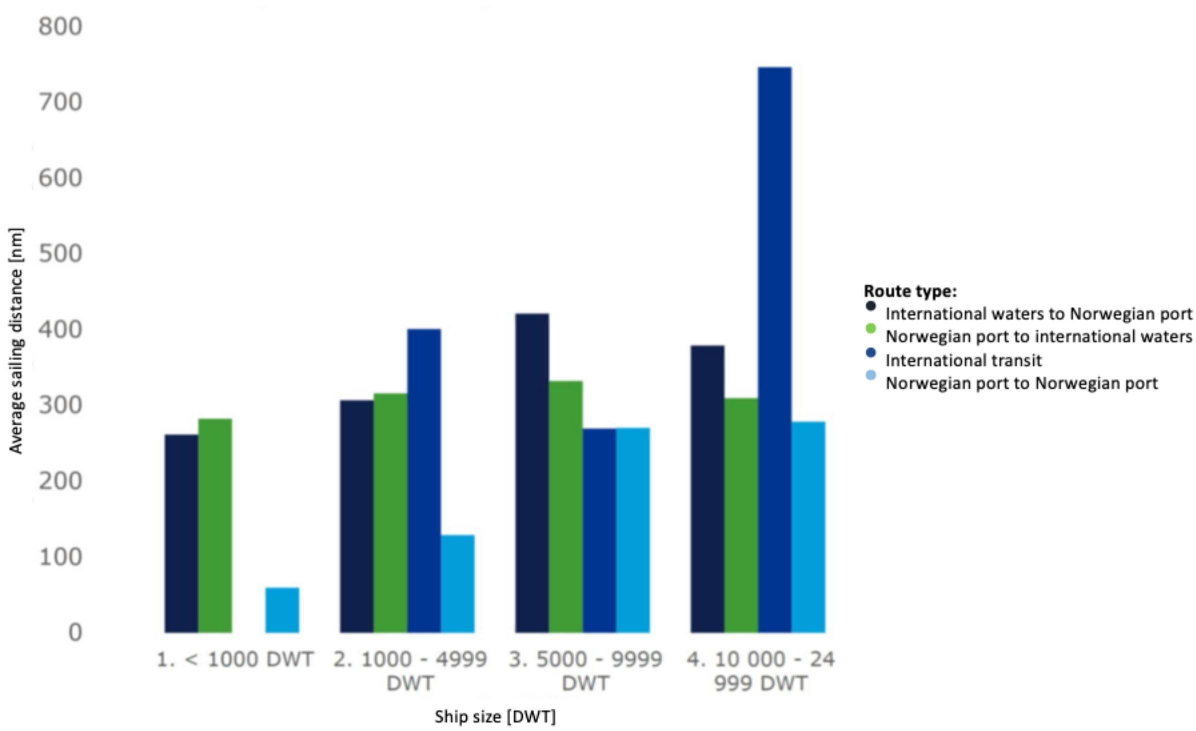


Figure 15.: Average sailing distance Norwegian shortsea bulk transport (Dale 2020, page 19)

will reduce the road traffic as well as reduce environmental impact per transported goods. The ambition is to move 30% of all goods transported longer than 300 km from the road to sea or rail by 2030. If this ambition is to be followed, the transportation demand for the domestic fleet will increase in the upcoming years.

4. Method description

One cannot foresee the future. One can however make assumptions about a possible future . Based on an assumed future, or a set of different possible futures, calculations on how the futures performs in different areas can be made.

The domestic bulk fleet's zero-emission potential depends among other things on the development of infrastructure. If the infrastructure for zero-emission fuels is poor, few voyages can be performed using zero-emission fuels.

This thesis is a combination of an IA and a scenario analysis. This chapter will introduce how these two methods are used.

4.1. Scenario analysis

According to the Cambridge dictionary, the definition of a scenario is: "one of several possible situations that could exist in the future" (Cambridge Dictionary n.d.[c]).

Scenario analysis is a good tool for asking "what if" questions. In addition to finding the most likely future, one can find the consequence of a future given that something specific happens - what if.

Scenario analysis is a good tool for use in decision making. In financial modelling, scenarios are typically used to estimate changes in cash flow due to potentially favourable and unfavourable events. Scenarios can define best- and worst-case futures based on specific events. The base-case scenario is the average scenario. The worst-case scenario considers the most serious or severe outcome that might happen. The best-case scenario models the ideal projected scenario (Corporate Finance Institute n.d.).

Scenarios change many variables at a time creating different states, unlike sensitivity analyses which only explore the change in one variable. Scenarios can include elements that cannot be modelled, such as new regulations and innovation. A common mistake in decision making is under- and over prediction. Scenario planning attempts to compensate for these errors. It can help to find a middle ground. This is done by dividing our knowledge into two areas (Schoemaker 1995, page 25-40): things we believe we know, and things we do not know or believe is uncertain.

Schoemaker defines the following steps for development of scenarios (Schoemaker 1995, page 25-40):

1. Define the scope
2. Identify the major stakeholders
3. Identify basic trends
4. Identify key uncertainties
5. Construct initial scenario themes
6. Check for consistency and plausibility
7. Develop learning scenarios
8. Identify research needs
9. Develop quantitative models
10. Evolve towards decision scenarios

First, the scope should be defined to know what type of information the scenarios should contain. This was performed in chapter 2 where the problem is defined. Here information about time-frame and market is given.

To gain insight into how the infrastructure will develop in the different scenarios, the main stakeholders should be defined. The stakeholders will make decisions based on the market situation. These decisions can affect infrastructure development. When the stakeholders have been defined, trends in the industry should be identified.

When developing scenarios, it is important to first get an overview of what is known and what is uncertain. The things that are known should be included in every scenario. The uncertain things should vary between the different scenarios. One way to divide this into different scenarios are to create a high and a low case scenario. All the positive elements are put in the high case scenario, and all the negative elements in the low case scenario. This will give two extremes. Most likely none of the extremes will happen. Instead, one pessimistic scenario with an overweight of the negative elements, and one optimistic scenario with an overweight of positive elements can be created.

The next steps in the Schoemaker approach are to check for consistency and plausibility and develop learning scenarios. In these steps you make sure you have a compelling storyline. Ensuring that trends are compatible with the given time frame, assumptions fit together and that the main stakeholders are not placed in a position they will not like and therefore withdraw from. For example, a shipowner will not tolerate too high fuel prices for too long. When a compelling storyline is created, learning scenarios can be developed. The learning scenarios create the theme of each scenario and ensure that each scenario gives the outcome of interest.

Now that the theme and wanted outcome of each scenario is defined, the needed extra knowledge must be gathered through additional research.

In the last two steps a quantitative model is created to analyse the result and outcome of each scenario. In this thesis the quantitative model will be the mathematical model described in chapter 5.

The model will be analysed using a computer model created in Python, see chapter 6. During these two steps the IA will be implemented. Each scenario will lead to a different number of voyages being able to run on hydrogen fuel. This will impact the fleet's total emissions development towards 2030.

The benefit of scenario analysis is that it can give insight into how the future might look. However, one cannot make a scenario for every possible future. Depending on how the result is intended to be used, the value of the result might be limited.

DNV's "Energy transition outlook" (DNV GL 2020) is a model-based forecast of the world's energy system until 2050. It presents one most likely scenario of the future. Presenting different values related to energy production, conversion, and consumption. The results are based on an assumed timeline reaching 2050.

Lloyd's Register, on the other hand, has created four possible future scenarios in their report on "Techno-economic assessment of zero-carbon fuels" (Lloyd's Register and UMAS 2020). The four scenarios represent different development in fuel price. An upper and lower bound development with or without a carbon price is assumed. The analysis is performed using a case study on an 82,000 dwt bulk carrier.

4.2. IA

According to the Cambridge Dictionary, the definition of impact is: "a powerful effect that something, especially something new, has on someone or something" (Cambridge Dictionary n.d.[b]). Another definition of impact is "Positive and negative, primary and secondary long-term effects produced by a development intervention, directly or indirectly, intended or unintended." (OECD 2010, page 24).

An IA is according to the International Association of Impact Assessment (IAIA) described as "the process of identifying the future consequences of a current or proposed action" (International Association of Impact Assessment n.d.).

With increasing focus on global warming, sustainability, and the environment, Environmental Impact Assessment (EIA) has become more important over the past years. The Norwegian government defines EIA as: "the analysis and evaluation of possible environmental impacts of proposed decisions or activities likely to cause significant effects on the environment." (Norwegian Ministry of the Environment 2003, page 2). The Cambridge dictionary defines EIA as "a study of the possible effects on the environment of a new project" (Cambridge Dictionary n.d.[a]).

EIA is normally used as a way to analyse the environmental effect of a new project in a decision making process. A widely used method for performing EIA is Life Cycle Assessment (LCA). LCAs look at the environmental impact of the total life cycle of a project. Looking at maritime fuel, this will be the well-to-wake emissions.

The Journal of Cleaner Production includes an article about "Assessment of full life-cycle air emissions of alternative shipping fuels" (Gilbert et al. 2018). For any alternative fuel to be a viable solution, a key criterion is that it can deliver an emission reduction over its full life cycle. The article presents a life cycle assessment concerning six emission types for different alternative fuels. "Life Cycle Assessment of LNG Fueled Vessel in Domestic Services" (Hwang et al. 2019) is another article that uses LCA for analysing the environmental effect of different fuels in shipping. The article compares the use of LNG as maritime fuel versus using diesel. The research was performed based on a case study of a 50K bulk carrier engaged in domestic services in South Korea. The analyses were performed based on five impact categories.

Instead of looking at the effect one action or one specific project has on the environment, the effect that one scenario has on the domestic fleet's CO_2 emissions will be analysed. Several impacts affect the environment. CO_2 is only one of these, but this thesis will only focus on CO_2 emissions. Optimally, the life cycle emissions should be analysed to get full insight into the overall impact of changing to a zero-emission fuel. However, due to LCA being a complex task and that the government's emission goal is measured in operational emissions, only the operational (tank-to-wake) emissions will be considered in this thesis.

5. Mathematical formulation

As described in chapter 4, this thesis will perform a scenario-based IA to see how hydrogen infrastructure development affects the domestic bulk fleet's zero-emission potential. This chapter will present a mathematical formulation of the problem.

5.1. System description

The system consists of a given number of voyages v based on historical data over a given period. Each voyage is performed by a vessel that travels between ports p.

The system shall calculate the operational emissions O_{vf} from the fleet over the given period with the defined fuel availability. The operational emissions O_{vf} given by equation 5.1 are the tank-to-wake emissions from the vessel performing the voyage using fuel f.

Whether a voyage can be performed using fuel f depends on fuel availability and vessel range for fuel f. Traditionally, the range is not a problem for the domestic bulk fleet since the vessels have a range significantly larger than a regular voyage distance. However, with the transition to low- or zero-emission fuels, the range is a challenge due to the lower energy density of these fuels. In addition, fewer ports will have the given fuel available. It is no longer enough that the vessel can reach the delivery port, it must also be able to reach a port with available fuel.

In this model five rules are defined and used in four conditions defining when a voyage can be performed using a given fuel f. The following sections will describe the model output together with these rules and conditions.

Figure 16 illustrates the connection between input, rules, conditions, and output.

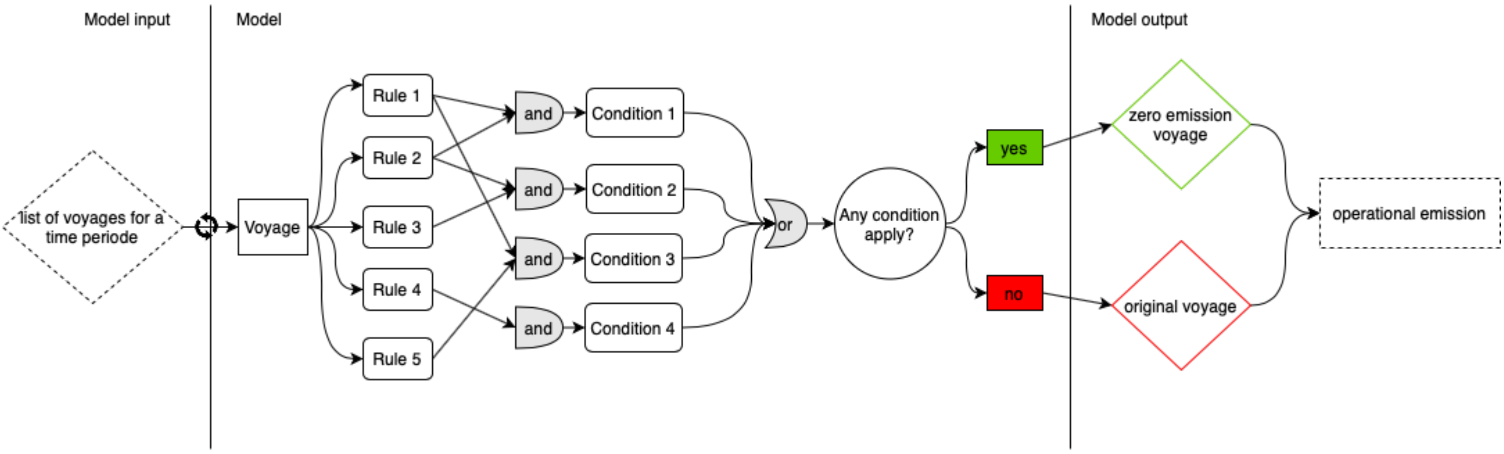


Figure 16.: Modelling process - relationship between rules and conditions.

5.2. Output

Table 5.1 gives an overview of the parameters used in the output function as well as the rules and conditions presented in the following sections.

Index	
v	voyages
f	fuel type
p	port
s	vessel
Set	
V	set of voyages
V_s	set of upcoming voyages for vessel s
F	set of fuels
P_f	set of ports with fuel f
Parameters	
O_{vf}	operational emissions for voyage v using fuel f
D_v	original sailing distance for voyage v
R_f	sailing range of vessel using fuel f
Da_{vp}	sailing distance from start port to tanking port p with fuel f in voyage v
Db_{vp}	sailing distance from tanking port p with fuel f to destination port in voyage v
X_{vf}	1 if voyage v uses fuel f, 0 otherwise
S_p	sailing range for fuel supply barge in port p
Variables	
a_{vf}	1 if destination port for voyage v has fuel f available, 0 otherwise

Table 5.1.: Parameters used in mathematical problem description

Based on the number of voyages v and the fuel f used during each voyage, the output function can be described as equation 5.1.

$$\sum_{v\in V}\sum_{f\in F} O_{vf} * X_{vf} \tag{5.1}$$

5.3. Rules for zero emission voyage

As illustrated in figure 16, five rules define four different conditions, of which at least one must be fulfilled if a voyage can be performed using a zero-emission fuel.

5.3.1. Rule 1 - vessel range

The first rule to be defined is the vessel range, which must be larger than the original voyage sailing distance, see equation 5.2.

$$R_{vf} \geq D_v, \quad v \in V \tag{5.2}$$

5.3.2. Rule 2 - fuel at destination port

Rule 2 apply if equation 5.3 is fulfilled. The equation states that the destination port for voyage v has fuel f available.

$$a_{vf} = 1, \quad v \in V \tag{5.3}$$

5.3.3. Rule 3 - next port within range

If equation 5.4 is fulfilled, rule 3 apply. This means that the vessel can reach the next port with fuel f available. Equation 5.4 sums the distance of the current voyage (D_v) with the distances of the upcoming voyages for the current vessel ($D_{v'}$).

$$D_v + \sum_{v'\in V_s} D_{v'} \leq R_f, \quad v \in V \tag{5.4}$$

5.3.4. Rule 4 - fuel port on the way to destination port

For an additional sailing distance, the vessel can fuel at a port p where fuel f is available on the way to the destination port. Then the sailing distance between the start port and fuelling port, as well as the sailing distance from the fuelling port to the destination port, must be less than or equal to the vessel range, see equations 5.5 and 5.6.

$$Da_{vp} \leq R_f, \quad v \in V, \quad p \in P_f \tag{5.5}$$

$$Db_{vp} \leq R_f, \quad v \in V, \quad p \in P_f \tag{5.6}$$

5.3.5. Rule 5 - destination port within range of fuel supply barge

For a given range from a port p with fuel f, it can be cost-efficient for a voyage using fuel f ending in another port with no fuel, to have fuel f transported to the arrival port. Illustrated by figure 17, the further away from port p the destination port is, the less favourable this becomes.

Rule 5 apply if equation 5.7 is fulfilled.

$$S_p \geq Db_{vp}, \quad v \in V, p \in P_2 \tag{5.7}$$

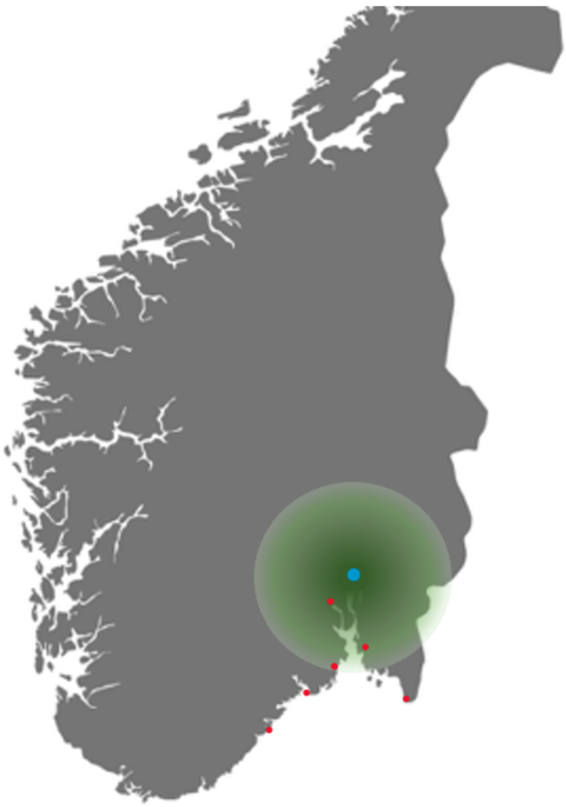


Figure 17.: Illustration of how far away from the hydrogen port it will be profitable to transport hydrogen. Blue dot illustrates a hydrogen port, red dots are other ports or quays.

5.4. Establishing zero-emission voyage conditions

Below follows four different conditions stating which of the five rules must be met for each condition if a voyage can use zero-emission fuel based on the given condition.

Condition 1: rule 1 + 2
Condition 1 states that the vessel range is larger than the voyage distance, and that hydrogen is available at the destination port.

Condition 2: rule 2 + 3
In condition 2 the vessel range is large enough to reach the next port with a zero-emission fuel available.

Condition 3: rule 1 + 5
Condition 3 states that the vessel range is larger than the voyage distance, and that the destination port is within range for the fuel supply barge.

Condition 4: rule 4
For condition 4 there is a hydrogen port on the way to the destination port, and the hydrogen port is within reach for the start and end port.

If none of the above conditions applies, the vessel will use the original fuel, and thus have the original emissions O_{vf}.

6. Developing a quantitative model using Python

Some problems arise when modelling the output and rules described in chapter 5 in Python. Due to data availability and program limitations, some simplifications must be made. This chapter will describe the process from the mathematical model to the program model. The chapter will define necessary assumptions and simplifications.

6.1. Input values

The main input values are a voyage table, combined with a port table.

The voyage table is created based on AIS data from the fleet selection defined in chapter 2. It describes each voyage performed by the fleet over a given period. For each voyage, the start and end port together with time and distance is given. In addition, the original operational emissions for each voyage is given. Figure 18 gives a simplified illustration.

IMO nr.	Start date	Start port ID	End port ID	Distance	CO2 emission

Figure 18.: Illustration of the voyage table used in the quantitative model.

The port table consists of a port ID for each port. This ID can be linked to the port ID in the voyage table. For each port, the port coordinates are given. The coordinates are needed to calculate the distances between the different ports. The port table will also give the fuel availability.

As mentioned in chapter 2, the system shall be analysed based on varying fuel availability. The model will be run for three different scenarios of fuel availability that will be described in chapter 7.

The vessel range when using hydrogen fuel will be significantly lower than when using fossil fuel. The vessels used in the voyage table have different size varying from 1500-25.000 dwt with an average size of 3300 dwt. However, as mentioned in section 3.3, shipowners are more likely to invest in ships within a size range of 3500-6500 dwt in the future. If zero-emission vessels are built, they will most likely be within that size range and have about the same range based on fuel. It is therefore assumed that all hydrogen voyages will have the same range limitation. Based on DNVs work with Felleskjøpet and HeidelbergCement as mentioned at the beginning of this thesis, the vessel range demand was set equal to 500 nm. The tender process showed that 500 nm seemed like a good balance between vessel size and fuel storage demand.

Once the input values are defined, the model will run through each voyage and check if the voyage can use hydrogen as a fuel or not. If one condition applies, the model will go to the next voyage. The conditions for using hydrogen fuel are the conditions defined in chapter 5 consisting of the rules defined in the same chapter, see figure 16. The following sections will go through how these conditions are modelled.

6.2. Condition 1

The first condition is the simplest. If the distance of the current voyage in the voyage table is less than the defined hydrogen vessel range, and the end port has hydrogen available, the voyage can be performed using hydrogen fuel. No additional calculation is needed for this condition.

6.3. Condition 2

If the first condition does not apply, the model checks if condition 2 might apply. If the first voyage has a short distance, the vessel might be able to reach the next destination port or the one after. All voyages for the given vessel are sorted out and the model investigates if the vessel can reach the next port on the vessel's agenda that has hydrogen available.

6.4. Condition 3

This condition states that the vessel range is large enough to reach the destination port. The destination port does not have hydrogen available, but is within a profitable range for a fuel supply barge as illustrated in figure 17.

6.4.1. Fuel supply range

The shipowner can accept a given increase in fuel costs to complete the voyage using green fuel. Since it is assumed that vessels running on hydrogen fuel have about the same size and the same range, it is also assumed that they will have the same fuel consumption. It is therefore also assumed that they will have the same limit for additional fuel costs. Due to high energy demand for compressing a small volume in a large tank, it is assumed that each time the vessel refuels, the vessel will fill 80% of the total tank capacity. The tank should ideally never contain less hydrogen than 20% of the total capacity.

Normally the fuel cost stands for about 20-25% of the operational costs of the vessel. Some increase in fuel cost is therefore acceptable. How large this acceptable increase is, depends on the hydrogen cost. Expensive hydrogen makes fuel cost a larger part of the operational cost. The acceptable increase will then be lower than for low hydrogen cost. The cost of hydrogen will vary each year, see values developed in connection to GSP in figure 42 in appendix B.

The average speed of the fleet is 9 knots. For a vessel with a size around 5000 dwt this speed gives a fuel consumption equal to about 30kg/hr. Refuelling the amount of hydrogen used for 400nm equals refuelling 1333kg of hydrogen.

The cost of fuel supply depends on transported volume and consists of an initial cost in addition to a cost based on transportation distance. When the cost of fuel supply exceeds the accepted additional fuel cost, fuel supply is not an option. A report from Aasheim Synergy in connection to GSP gives the cost of fuel supply per nm, see appendix A.

6.4.2. Modelling fuel supply range

Since the fuel supply distance is assumed to be quite small, it is assumed that it is sufficient to look at the shortest distance between the two ports, a straight line. This is the ground distance not taking the sea route into account.

In a coordinate system, the easiest way to calculate the distance between two points is by using Pythagoras formula. Due to the earth curvature, Pythagoras formula will have an increased margin of error as the distance between the two coordinates increases. To reduce the margin of error, the geographical distance is therefore calculated. In the Python module geopy, two methods for geographical distance calculation exist, geodesic distance or the great-circle distance. The great-circle distance assumes that the earth is a perfect sphere. Due to rotation, the earth has a more ellipsoidal shape, which is accounted for using geodesic distance.

For each port with hydrogen available, the shortest distance to the destination port is calculated. If this distance is smaller than the profitable range for fuel supply, the destination port can be reached with a fuel supply barge and the voyage can be performed using hydrogen fuel.

6.5. Condition 4

If none of the above conditions applies, the model will check if condition 4 applies. In this condition, the model looks for the possibility that the vessel can refuel on the way to the destination port. It is assumed that refuelling only is profitable once per trip.

The approach illustrated in figure 19 is used to check if there is a hydrogen port in between the start and end port. By defining a circle which extends from each port with a radius equal to the distance between the two ports, an area that lays between the two ports is defined. Then, the model checks if there is a hydrogen port laying within this area. This is a simplification that does not take the earth's geography into account. If there, for instance, is a fjord between the two ports, it can be a significant deviation even though the port lays within the defined area. However, this is assumed to be a sufficient simplification as the total distance also will be a limitation.

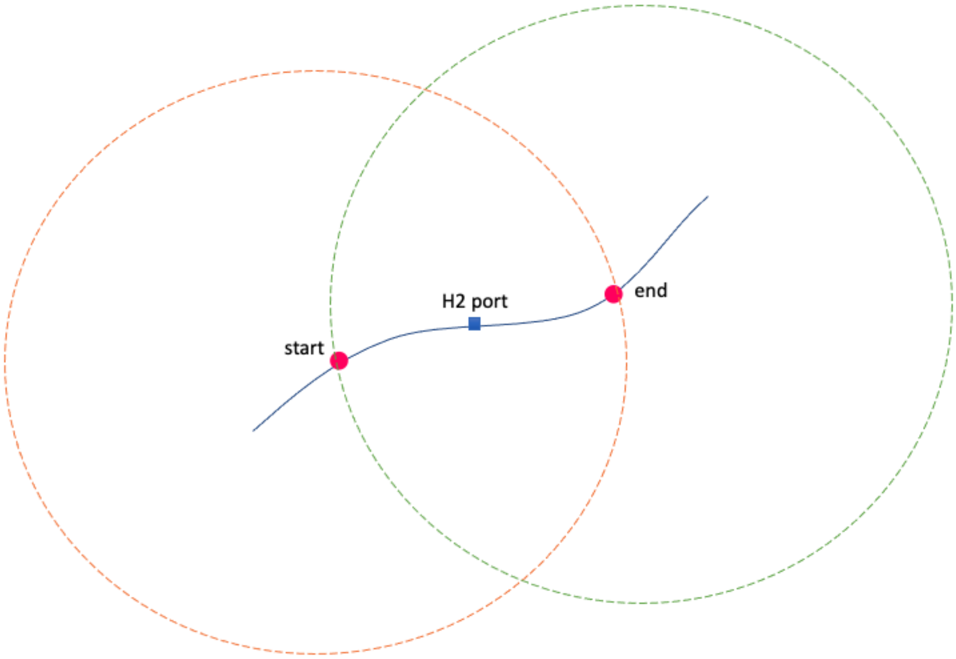


Figure 19.: Illustration of how it is determined if a port is in between two ports.

If no hydrogen port lays within the defined area, condition 4 is not an option and the voyage will not be able to run on hydrogen fuel. If there is a hydrogen port that lays within the defined area, the model continues to check if there is an option to refuel on the way.

To do so, the actual distance between the start port and hydrogen port, as well as the distance between the hydrogen port and end port must be calculated. Since these distances can be quite large, assuming the shortest distance will, in many cases, give a large margin of error. If the voyage, for example, passes by a fjord, the extra distance might be significant. In some cases, this path will cross land area. For routes going from the east to the west coast of Norway, this distance is significantly shorter than the sea route. Therefore, a more careful calculation should be carried out. However, this is not straightforward. There is a balance between accuracy and profitability, or accuracy and time consumption.

Kystverket (Kystverket n.d.) has a tool with route info that defines routes between ports. The tool consists of "highway routes" following the coast, and smaller supply routes going from ports and fjords to the highway route. Using this tool one can combine routes to define and calculate the distance to every route between Norwegian ports. The tool is created as a navigational aid. However, since the routes consist of coordinates they can also be used for calculations.

6.5.1. Calculate distance with route info from Kystverket

The route data from Kystverket is provided as waypoints in xml files. Each route has one file with several coordinates represented as waypoints that describe the route.

Even though this tool theoretically can be used to define the route between every port along the Norwegian coast, using it is more difficult for multiple reasons.

- The routes are not connected to a specific port, or to the port info provided by DNV. This makes it hard to connect routes to ports, see figure 20.

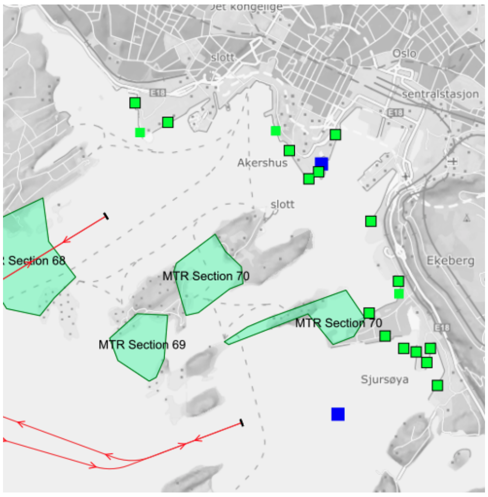


Figure 20.: Connection between route and port, Kystverket route info (Kystverket n.d.)

- The highway routes pass by ports, meaning that one coordinate in the middle of the route might be the closest coordinate for the given port
- The different routes do not start and end in the exact same coordinates, see figure 21 making it difficult to combine routes.

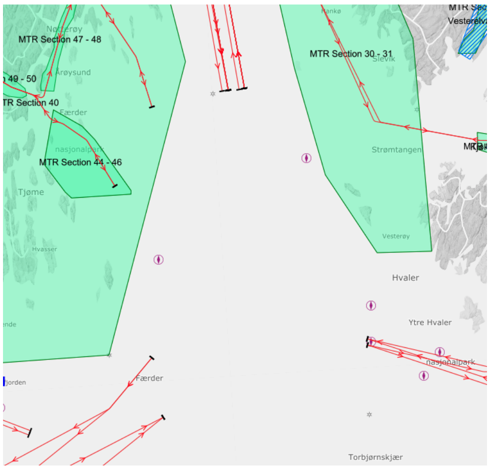


Figure 21.: Connection between routes, Kystverket route info (Kystverket n.d.)

With over 500 routes it is a time-consuming task to run through each coordinate in each route to find the best route for each voyage. The job will be even more time consuming if combined routes are needed. Some simplifications are therefore made and the next paragraphs will describe the modelling approach.

Optimally, multiple routes should be combined to get the most accurate result. However, in many cases, the supply routes are almost straight out from the port as shown in figure 22. Therefore, only one route is used. The total sailing distance then becomes the route distance combined with the shortest connection distance at each end. This is done to save significant calculation time since the route combination will be time-consuming work.

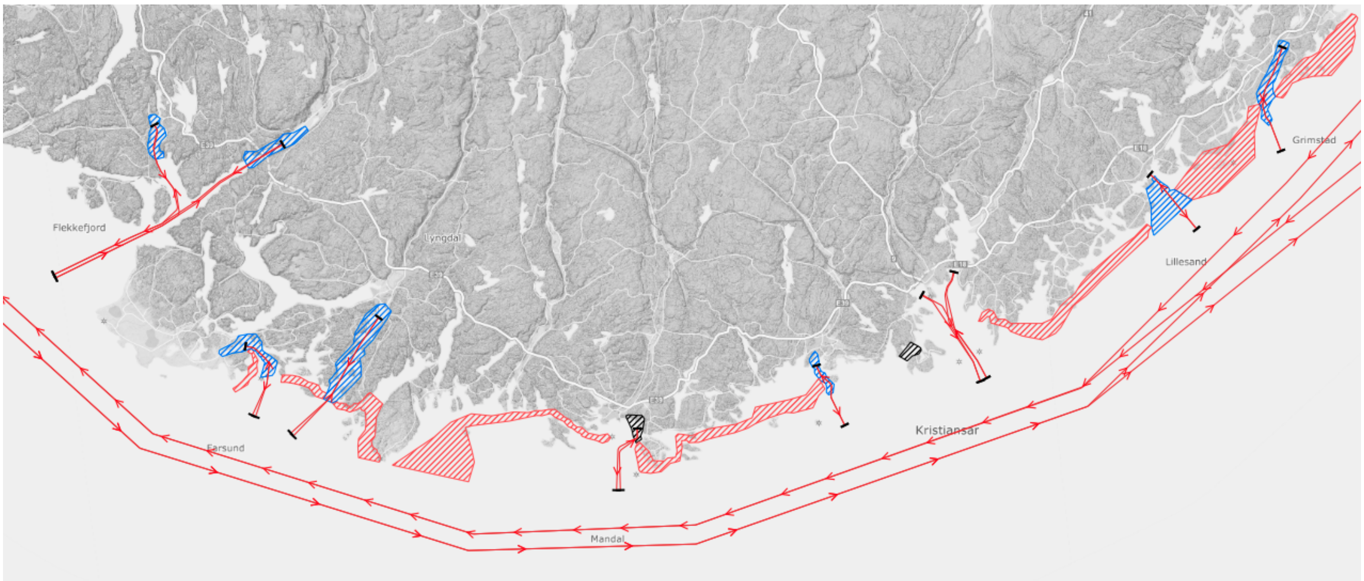


Figure 22.: Illustration of highway routes and supply routes from Kystverket route info (Kystverket n.d.)

There will, however, be some additional distance using the straight line instead of the actual route. Initially, it was assumed that the deviation was negligible. However, figure 23 gives some examples showing that the average deviation is 8%. Therefore, an error margin of 8% should have been added to the total sailing distance.

Filename	xml file distance	shortest path	deviation
NCA_Lyngdal_In_20201001.rtz	8.118003796	8.085240794	0.4%
NCA_Flekkefjord_In_20201001.rtz	13.02082148	10.03401819	23%
NCA_OsloEast_In_20201001.rtz	46.82787339	43.16316206	7.8%
NCA_Sauda_Skudefjorden_In_20210212.rtz	48.07270805	45.60000224	5%
NCA_Namsos_Rekkoyrasa_In_20200615.rtz	25.5367073	23.06762554	9.7%
NCA_Surnadal_Grip_In_20200615.rtz	36.27126218	32.0374307	12%
NCA_Sandefj_Bonden_In_20201001.rtz	8.974170295	8.928165537	0.5%
NCA_Dirdal_Skudefjorden_In_20210212.rtz	32.3419995	28.62010779	11.5%
NCA_Rognan_Saltstr_Fleinvaer_In_20210212.rtz	52.54893766	45.78426981	13%
NCA_Kvinesdal_In_20201001.rtz	14.53420529	14.52701305	0.05%
Average			8%

Figure 23.: Deviation between xml file distance calculation and shortest path distance.

Connecting route to port is done using the same approach as for fuel supply in section 6.4. To save time and not have to open the xml files each time, the start and end coordinate of all routes are stored in a table. Then the distance from the port to each route start/end is found for both start and end port. This gives two lists. One list for the connection distance from the start port to each route, and one for connection distance from the end port to each route. Combining these two lists gives one list with the total connection distance to each route.

However, as mentioned above, the closest connection coordinate for each route may not be the start or end coordinate of a route.

To save calculation time, it is assumed that one of the top five routes in the "total connection" list will have the closest connection coordinate. Therefore, only the files for the top five routes are opened and analysed to find the nearest connection coordinate. Now a new total connection distance list can be created. The total sailing distance of the closest route is calculated.

If no route is found, the distance between the two ports is equal to the shortest surface distance.

The flow chart in figures 24 and 25 illustrates the solution approach for the distance calculation problem.

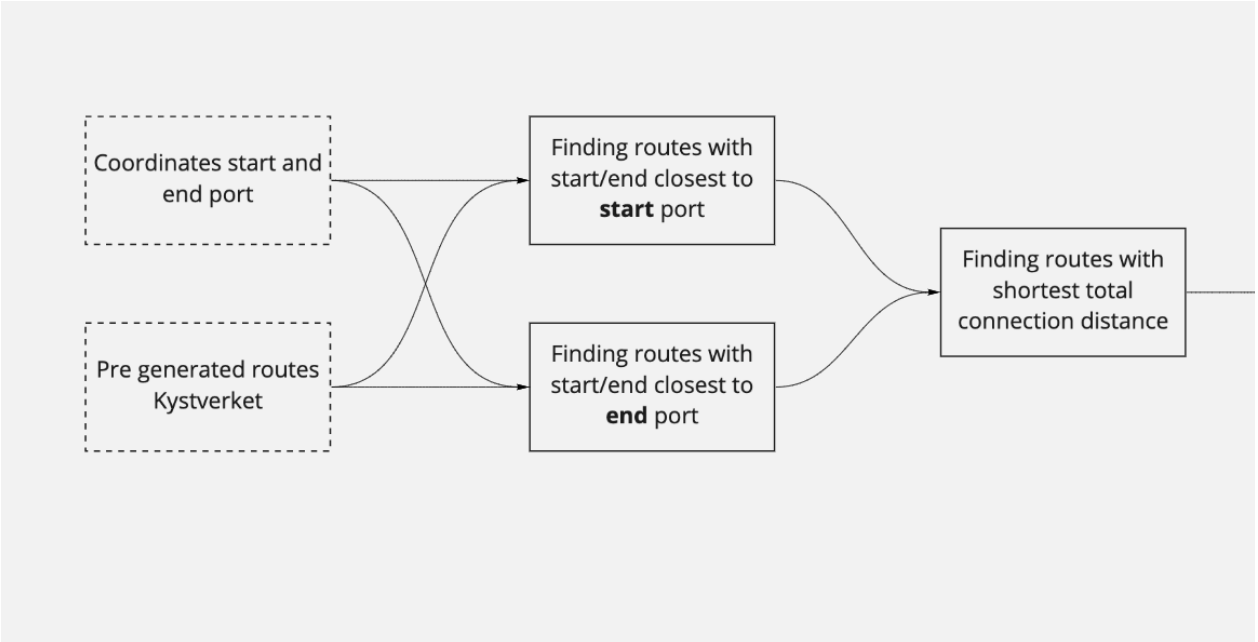


Figure 24.: Flowchart for modelling voyage distance part 1

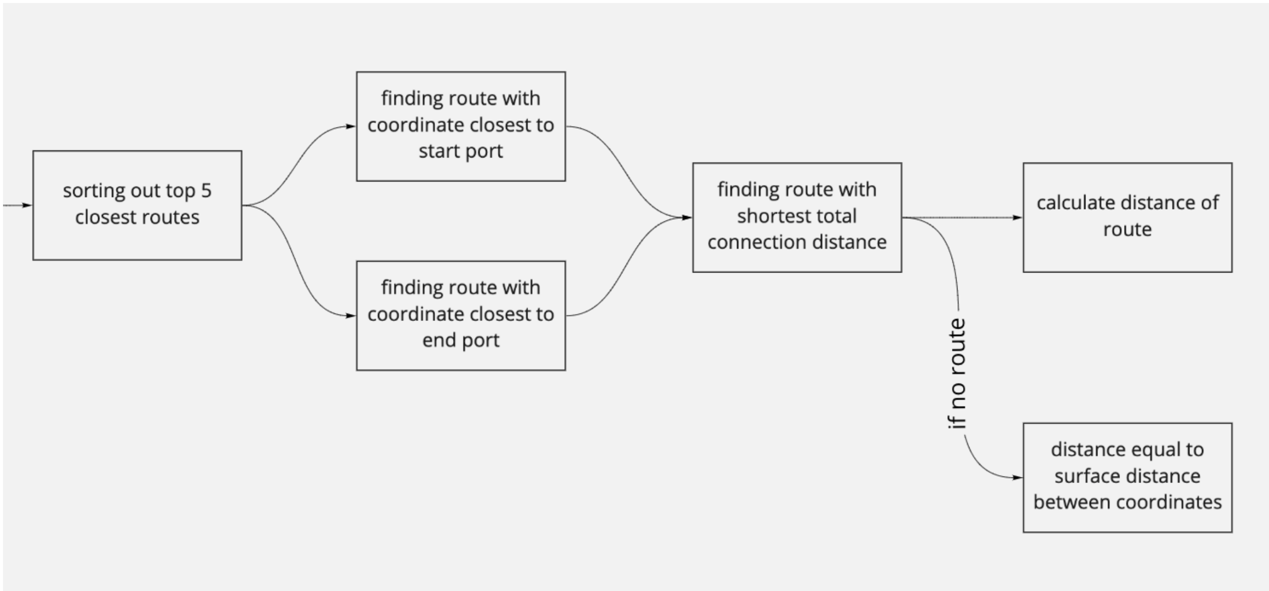


Figure 25.: Flowchart for modelling voyage distance part 2

6.5.2. Use of route calculation in main model

Section 6.5.1 describes how the distance between two ports can be calculated using Kysteverkets route info tool. Even though some simplifications are made, the process of calculating distance using this approach is still very time-consuming. To save calculation time in the main model a database storing the distance between each port in Norway is created. Then the main model can read the distance from this database instead of running the calculation program for each voyage where condition 4 is an option.

The calculation time for calculating the distance between two ports is about three seconds with the program created as described in section 6.5.1. With about 2000 ports and quays to calculate the distance between, the database would take about 70 days to create.

In the main model, the distance between two ports is not used directly. It is only used to check if the distance is larger than the vessel range, see equation 5.5. Calculating the distance between two ports using the shortest path is significantly less time consuming than the programme in section 6.5.1. For every case where it is assumed that the shortest path method does not give a distance shorter than the vessel range, while the calculation programme will give a distance larger than the vessel range, the shortest path distance is used. The assumed situations where this is the case are as follows:

- The database is first filled with the actual distances between ports taken from AIS data in the voyage table. The distance between ports that are never used in the voyage table is defined as larger than the vessel range. None of these distances will be used or relevant for the fleet analysed in this thesis.
- All cases where the shortest path distance is larger than the vessel range the shortest path is used. The actual distance will always be larger than the shortest path distance. The actual distance will therefore in these cases be larger than the vessel range.
- For ports where the shortest path distance is less than 100 nm the shortest path is used. It is assumed that this will ensure that the actual distance still does not exceed the vessel range, see figure 26 where the shortest path is about 100 nm and the actual distance is 490 nm.
- All cases where both ports are either east or west for Mandal or north of Namsos, the shortest path is used.

The simplifications above will give a large margin of error for the actual sailing distance. However, it should not give that large deviation between the number of cases where the sailing distance is either less or greater than the vessel range compared to using the calculation model on every distance. The simplification reduced the calculation time to a couple of days, and as mentioned at the beginning of this chapter, there is a balance between accuracy and profitability.

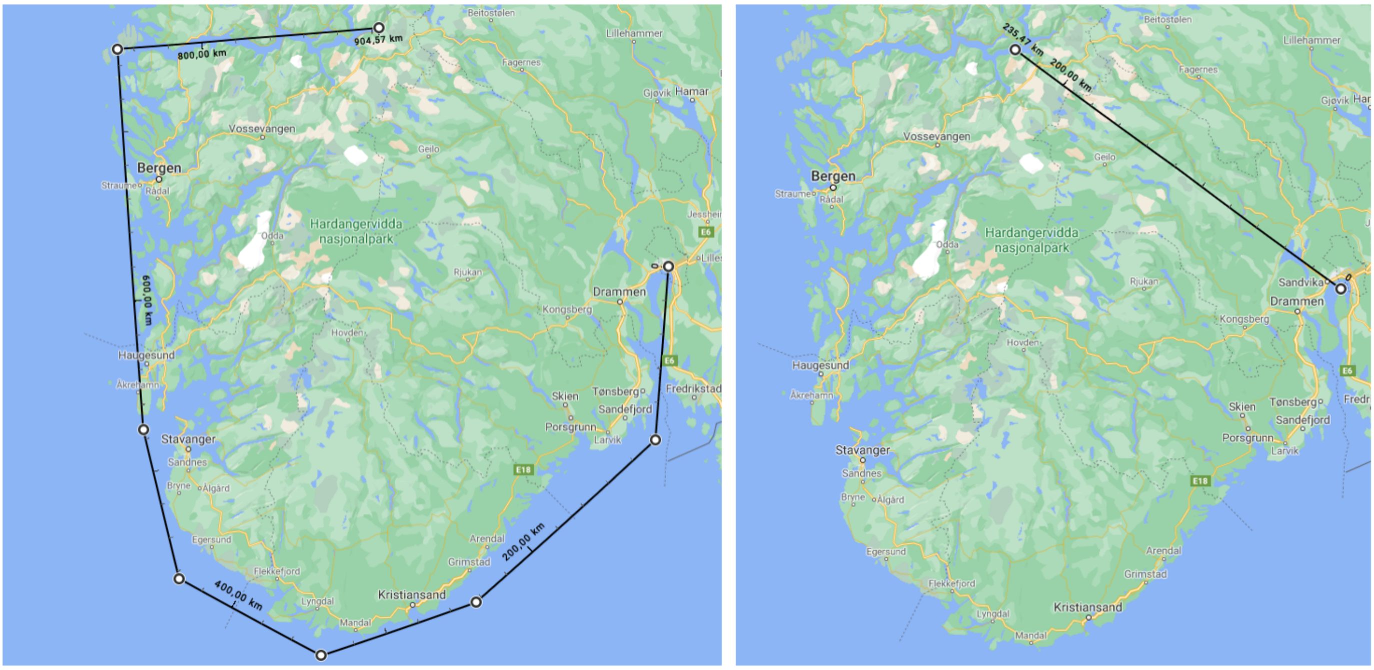


Figure 26.: Illustration of shortest path versus actual sailing distance.

6.6. Fleet volume limitation based on assumed production volume

Each production facility delivering hydrogen to the different ports will have a given production rate in tons/day. There will therefore be a limitation to how much volume each port can deliver at a given time.

To model this, the model needs to know the amount of hydrogen available in a given port at a given point in time. This is done by adding two columns to the fuel availability table. One column that gives the time at which the storage last was used, and another column that shows the amount of hydrogen available after the last vessel refuelled at the given port. When a new vessel arrives for refuelling, the time that has passed since the last vessel arrived is calculated, and the amount of hydrogen that has been produced in this period is added to the storage. If the amount of hydrogen available in storage is less than what is needed to completely refuel the vessel, the vessel cannot refuel in the given port.

This modelling approach does not account for limitations to storage capacity in port.

7. Developing scenarios for future hydrogen infrastructure development

This chapter will describe the process of developing the scenarios that are going to be the input values for the model described in the previous chapter. The process is based on the literature introduced in chapter 4. However, the approach will not be identical due to available information and system boundaries. The steps are used as a tool in understanding what each scenario should contain and to provide awareness of what each of them should answer.

7.1. Main stakeholders in fuel infrastructure development

There are mainly four stakeholders to consider when looking at fuel for maritime transport. They are the fuel producers, cargo-owners, shipowners, and ports. They all have a play in how the industry develops.

When building a new vessel, shipowners must decide what type of vessel they want to build. If they want to build a zero-emission vessel they need to know where the zero-emission fuel they are going to use will be available, and at which price. In a transition phase, they may accept a higher building and operational cost. However, they must still be able to profit from the vessel. In Norway today, Enova provides investment support to zero-emission projects. Yet there still is a large demand for equity. Only larger shipowners and their financing partners have this equity. For smaller companies, it will be hard to enter the market as they have trouble getting high loans from the bank due to large uncertainty and small economical margins in domestic shipping. If the building and operational cost stay high, even the larger companies will have economical trouble with zero-emission vessels.

If cargo owners have a sustainability strategy and start making demands for reduced emissions from the vessel they use, cargo-owners have the power to push the industry in a greener direction. If they in addition are willing to pay somewhat more for greener vessels, more shipowners will be willing and able to invest in greener vessels.

Fuel producers are elementary if one is considering building a zero-emission vessel. Without available fuel, the vessel will not be able to operate.

There must be enough ports that are willing to provide the necessary areas and facilities to supply the fuel to the vessels. The amount of hydrogen the ports can store is an important factor and may change over time. The ports must also have enough capacity for the number of vessels arriving in order to minimise the waiting time.

7.2. Trends and uncertainties in domestic shipping

Little is known about the future development towards a zero-emission fleet other than that such a development is necessary. Today, no fuel stands out as the best solution and there are still many obstacles to overcome before a sustainable zero-emission fleet is in operation.

The Norwegian government has defined a goal to reduce the emissions from the domestic fleet by 50% within 2030. A considerably increased CO_2 tax will most likely be introduced, however, there are large uncertainties about how large this tax will be. There are several initiatives to speed up the development of a greener domestic shipping industry such as GSP and Enova.

According to (Tomasgard et al. 2019) hydrogen has multiple areas of use in a zero-emission society. In addition to being an energy carrier for the transportation sector, it can be used in power and heat production and as storage for surplus energy from renewable energy production.

One of the reasons why hydrogen is relevant as an energy carrier is the connections between the different sectors. In Norway, the connection between the power and transportation sector is especially important. Electrification through battery and fuel cells can reduce the emissions from the transport sector. However, this will increase the electricity demand and may lead to power challenges. Hydrogen can be used as energy storage to even out the load. Energy from wind and solar power is only produced when the sun shines or the wind blows, not necessarily when it is needed. Increased production of renewable energy will increase the demand for energy storage to optimise the utilisation and value of variable renewable energy sources(Tomasgard et al. 2019).

Compressed hydrogen is not profitable to transport over a large distance. Therefore local production is more relevant.

In an optimised situation for the domestic fleet, the location of hydrogen filling facilities should be based on the fleet's operational pattern. However, this will not be the case. Hydrogen availability for maritime use will not only depend on hydrogen demand as a fuel, but hydrogen demand in all sectors in Norway. The fleet must therefore adjust to where hydrogen will be available based on the development of overall hydrogen demand in Norway.

7.3. Scenarios

Three different scenarios has been developed. The first scenario is a base-case scenario and is the most likely scenario based on today's knowledge and assumptions for the future. Two additional scenarios are created; one low- and one high availability scenario. The low- and high availability scenarios represent a more pessimistic and optimistic version of the future, respectively.

Figure 3 in chapter 2 describes the model input. The model input values are the fleet operational pattern and hydrogen development. The fleet operational pattern is based on historical data and therefore assumed known and the same for every year in all scenarios. Hydrogen availability development, however, will change. This is what each of the following scenarios should contain.

In a balanced market, the amount of hydrogen produced and delivered to each port is equal to the demand at the given port. However, early in an emerging market, there might be a transformation phase where the volume delivered will be lower than the demand. This gives a supply limitation to the fleet. Even though the voyage theoretically based on hydrogen availability location can be performed using hydrogen, there is not enough hydrogen available at the given locations. This effect is important to include in the different scenarios by defining the production rate at each location.

A mapping of upcoming projects for the production of compressed hydrogen has been performed by GSP (2021), see figure 27. This resulted in a total of 20 projects. Each project is connected to the closest port. The amount of hydrogen produced each year will for many of the projects increase towards 2030.

Port	County	2024	2025	2026	2027	2028	2029	2030
Berlevåg	Finmark	1	3	5	10	10	10	10
Bodø	Norland	1	2	3	5	5	5	5
Finnsnes	Troms	10	10	10	10	10	10	10
Tau	Rogaland	2	3	3	3	3	3	3
Florø	Vestland	2	3	4	5	6	7	8
Glomfjord	Nordland	2	3	5	6	7	8	9
Hellesylt	Møre og Romsdal	1	2	3	4	5	6	7
Karmsund	Rogaland	3	4	5	6	7	8	9
Kollsnes	Vestland	0.5	4	4	4	14	14	14
Kristiansund	Møre og Romsdal	3	4	5	6	7	8	9
Kristiansand	Agder	1	2	2	2	2	2	2
Holmestrand	Viken	5	7	9	11	13	15	17
Sandnessjøen	Norland	2	3	4	4	4	4	4
Mo i Rana	Nordland	10	10	10	10	10	10	10
Mongstad	Vestland	3	4	5	6	7	8	9
Odda	Vestland	5	8	11	14	17	20	20
Porsgrunn	Vestfold og Telemark	5	8	11	14	17	20	20
Nordfjord	Agder	1	2	2	2	2	2	2
Risavika	Rogaland	1	2	3	5	5	5	5
Årdalstangen	Vestland	2	3	5	7	9	11	13
		60.5	**87**	**109**	**134**	**160**	**176**	**186**

Figure 27.: Production development in tons/day for compressed hydrogen in Norway (GSP, 2021)

The 20 projects and their locations will be used in the scenarios. However, the volume produced from each project at a given time, and when each project begins production, will vary between the different scenarios.

The next three sections will describe each scenario. Each scenario will start in 2024 assuming this is the first year with significant availability of hydrogen. The scenarios will end in 2030 as this is the measuring point.

7.3.1. Base-case scenario development

Figure 28 gives the aimed production for each project in the base-case scenario.

Port	County	2024	2025	2026	2027	2028	2029	2030
Berlevåg	Finmark	0.5	1.5	2.5	5	5	5	5
Bodø	Norland	0.5	1	1.5	2.5	2.5	2.5	2.5
Finnsnes	Troms	5	5	5	5	5	5	5
Tau	Rogaland	1	1.5	1.5	1.5	1.5	1.5	1.5
Florø	Vestland	1	1.5	2	2.5	3	3.5	4
Glomfjord	Nordland	1	1.5	2.5	3	3.5	4	4.5
Hellesylt	Møre og Romsdal	0.5	1	1.5	2	2.5	3	3.5
Karmsund	Rogaland	1.5	2	2.5	3	3.5	4	4.5
Kollsnes	Vestland	0.25	2	2	2	7	7	7
Kristiansund	Møre og Romsdal	1.5	2	2.5	3	3.5	4	4.5
Kristiansand	Agder	0.5	1	1	1	1	1	1
Holmestrand	Viken	2.5	3.5	4.5	5.5	6.5	7.5	8.5
Sandnessjøen	Norland	1	1.5	2	2	2	2	2
Mo i Rana	Nordland	5	5	5	5	5	5	5
Mongstad	Vestland	1.5	2	2.5	3	3.5	4	4.5
Odda	Vestland	2.5	4	5.5	7	8.5	10	10
Porsgrunn	Vestfold og Telemark	2.5	4	5.5	7	8.5	10	10
Nordfjord	Agder	0.5	1	1	1	1	1	1
Risavika	Rogaland	0.5	1	1.5	2.5	2.5	2.5	2.5
Årdalstangen	Vestland	1	1.5	2.5	3.5	4.5	5.5	6.5
		30.25	**43.5**	**54.5**	**67**	**80**	**88**	**93**

Figure 28.: Production development in tons/day for compressed hydrogen in Norway for the base-case scenario.

The production in figure 28 will be 50% of the actual hydrogen production at each location based on the values from GSP (2021). All the hydrogen produced will probably not be available for the domestic bulk fleet. Some will be used in other parts of the global fleet such as for offshore supply vessels, cruise industry or ferries. Some of the hydrogen will also be used in other industries such as ammonia production or energy storage for the grid. It is therefore assumed that only 50% of the hydrogen produced will be available for the domestic bulk fleet in the base-case.

In addition to the known projects, the hydrogen price development will affect the range of fuel supply. This range will affect the number of ports that can offer hydrogen. The hydrogen price development reaching 2030 is given in figure 42 in appendix B based on data from GSP. In 2024 it has been assumed that an 8% increase in fuel cost is acceptable. This gives a profitable fuel supply range equal to 18 nm based on the fuel supply cost given in a report from GSP performed by Aasheim Synergy, see figure 41 in appendix A. Figure 29 shows how much of the coast this range covers. As the hydrogen marked develops the willingness to pay an additional cost for fuel will go down. The range of fuel supply is therefore kept constant for all the years.

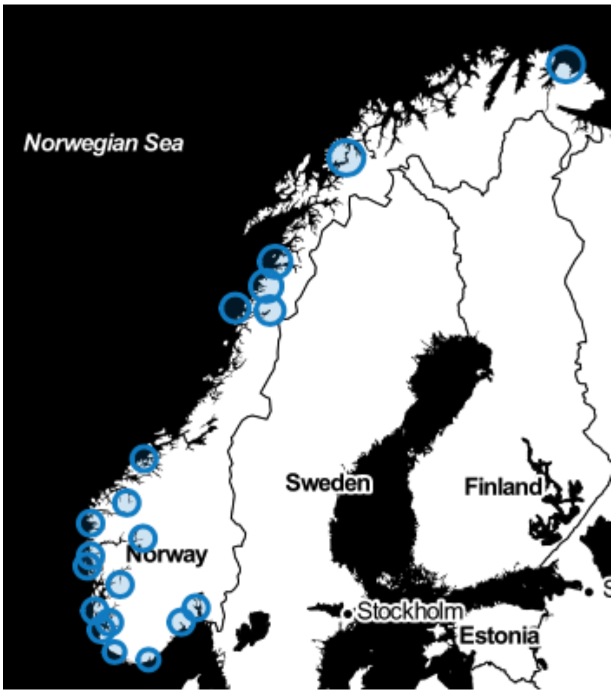


Figure 29.: Coastal coverage for fuel barge range 18 nm

7.3.2. Low availability scenario development

For the low availability scenario, it is assumed that the amount of hydrogen available at each of the 20 ports from the base-case scenario is reduced by 50%. Then only 1/4 of the hydrogen in figure 27 will be available for the domestic bulk fleet. In addition, it is assumed that there will be a significant delay in the facility development. First in 2028, all 20 ports from the base-case will have hydrogen available, and in 2024 only 10 ports will have hydrogen available compared to 20 in the base-case. The facility development for the low availability scenario looks as in figure 30.

Port	County	2024	2025	2026	2027	2028	2029	2030
Berlevåg	Finmark	0.25	0.75	1.25	0.75	1.25	2.5	1.25
Bodø	Norland				0.25	0.5	0.75	2.5
Glomfjord	Nordland	0.5	0.75	1.25	3	3.5	4	4.5
Sandnessjøen	Norland		0.5	0.75	1	2	2	2
Mo i Rana	Nordland			2.5	2.5	2.5	5	5
Finnsnes	Troms	2.5	2.5	2.5	5	5	5	5
Tau	Rogaland	0.5	0.75	0.75	1.5	1.5	1.5	1.5
Karmsund	Rogaland		0.75	1	1.25	3	3.5	4
Risavika	Rogaland	0.25	0.5	0.75	2.5	2.5	2.5	2.5
Florø	Vestland					0.5	0.75	1
Kollsnes	Vestland	0.125	1	1	2	7	7	7
Mongstad	Vestland			0.75	1	1.25	3	3.5
Odda	Vestland	1.25	2	2.75	7	8.5	10	10
Årdalstangen	Vestland				0.5	0.75	1.25	3.5
Porsgrunn	Vestfold og Telemark			2.75	7	8.5	10	10
Holmestrand	Viken	1.25	1.75	2.25	5.5	6.5	7.5	8.5
Kristiansund	Møre og Romsdal					0.75	1	1.25
Hellesylt	Møre og Romsdal	0.25	0.5	0.75	2	2.5	3	3.5
Kristiansand	Agder			0.25	0.5	0.5	1	1
Nordfjord	Agder	0.25	0.5	0.5	1	1	1	1
		7.125	**12.25**	**21.75**	**44.25**	**59.5**	**72.25**	**78.5**

Figure 30.: Production development in tons/day for compressed hydrogen in Norway for the low availability scenario

The projects removed compared to the base-case is based on an assumption that projects from all the regions partly will emerge as planned, and partly be delayed. An analysis of which projects is most likely to be delayed has not been performed.

For the low availability scenario, it is assumed that fuel supply will not be a possibility. Condition 3 described in section 6.4 is therefore removed from the model for this scenario.

7.3.3. High availability scenario development

Figure 27 gives the aimed production for each project in the high availability scenario.

The high availability scenario is developed to give an optimistic view of the future. Assuming everything goes a little better than planned. Therefore, it is assumed for the high availability scenario that the amount of hydrogen produced will be larger than the companies assume. The amount of hydrogen available for the domestic bulk fleet is therefore assumed to be the amount the companies are planning to produce, that is two times the volume used in the base-case.

Further, it is assumed that the cost of hydrogen is reduced compared to the base-case. With lower initial costs for hydrogen, the initial profitable range for the fuel supply barge can be larger. It is therefore assumed that for the high availability scenario the profitable range of fuel supply will be two times the range used in the base-case. This gives a profitable range of fuel supply equal to 36 nm for the high availability scenario. Figure 31 shows how large part of the cost this range covers.

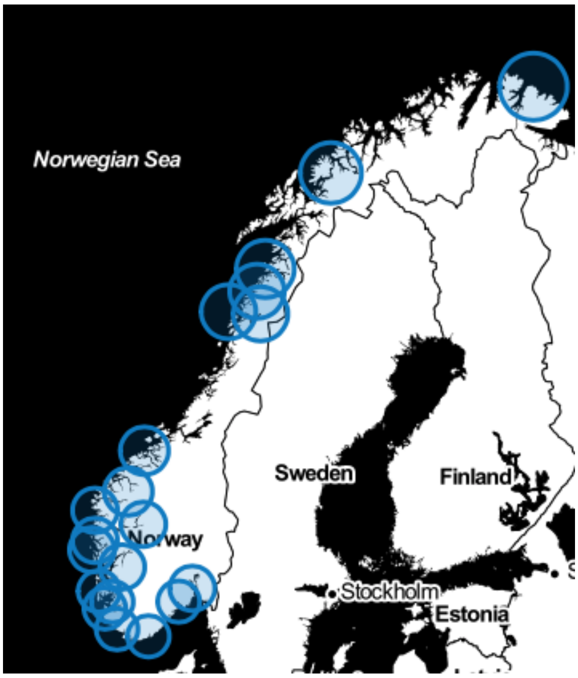


Figure 31.: Coastal coverage for fuel barge range 36 nm

8. Scenario-based impact assessment

The original emissions from the existing fossil-based fleet under consideration are as described in chapter 2 based on AIS data from 2019. In 2019 the emissions from the fleet selection were 247 926 tons CO_2. The reference year for the government's emission goal is 2005. Due to little available AIS data from this time, 2019 is used as reference year. With a high average age in the fleet, it is assumed that there is little change in the fleet between 2005 and 2019. Therefore 2019 emissions are assumed to be the same as the 2005 numbers. Based on this assumption, the emissions from the given fleet selection should be reduced by 50% to 123 963 tons CO_2 within 2030 in order to reach the government's emission reduction goal.

The following sections will provide results from the IA performed using the scenarios described in chapter 7. The results will show the emission reduction potential of the fleet based only on infrastructure developments for compressed hydrogen. The results will therefore assume that if the infrastructure exists, so will the needed number of vessels able to run on hydrogen.

8.1. Impact assessment base-case scenario

The base case scenario is assumed to be the most likely scenario. The background for this scenario development is described in section 7.3.1. The table in figure 32 gives the results from the base-case IA. From a total of 32 039 voyages, 22 322 can be performed using compressed hydrogen as fuel in 2030. This leads to a 62% reduction in CO_2 emission compared to 2019.

Year	CO2 emission [MT]	Reduction [%]	fuel supply radius[nm]	nr. Of H2 ports	Nr of H2 voyages	H2 voyage condition 1	H2 voyage condition 2	H2 voyage condition 3	H2 voyage condition 4
2019	247926	0			0				
2024	191390	23%	18	20	6890	993	1743	1987	2167
2025	164882	33%	18	20	9984	1225	2197	3121	3441
2026	144012	42%	18	20	12200	1380	2525	3683	4612
2027	124495	50%	18	20	14234	1583	2912	4177	5562
2028	102594	59%	18	20	16995	1748	3232	5213	6802
2029	97831	61%	18	20	17917	1845	3418	5522	7132
2030	95043	62%	18	20	18488	1942	3565	5795	7186
2030 no fuel supply option									
2030	102906	58%	0	20	16759	4132	4132	0	10347

Figure 32.: Results from IA of base-case scenario

The graph in figure 33 shows the emission reduction development for this scenario.

The figure shows that for the base case scenario, the domestic fleet can based on infrastructure developments for compressed hydrogen, reach a 50% reduction in CO_2 by 2027. Already in 2024, the emission can be reduced by 23%.

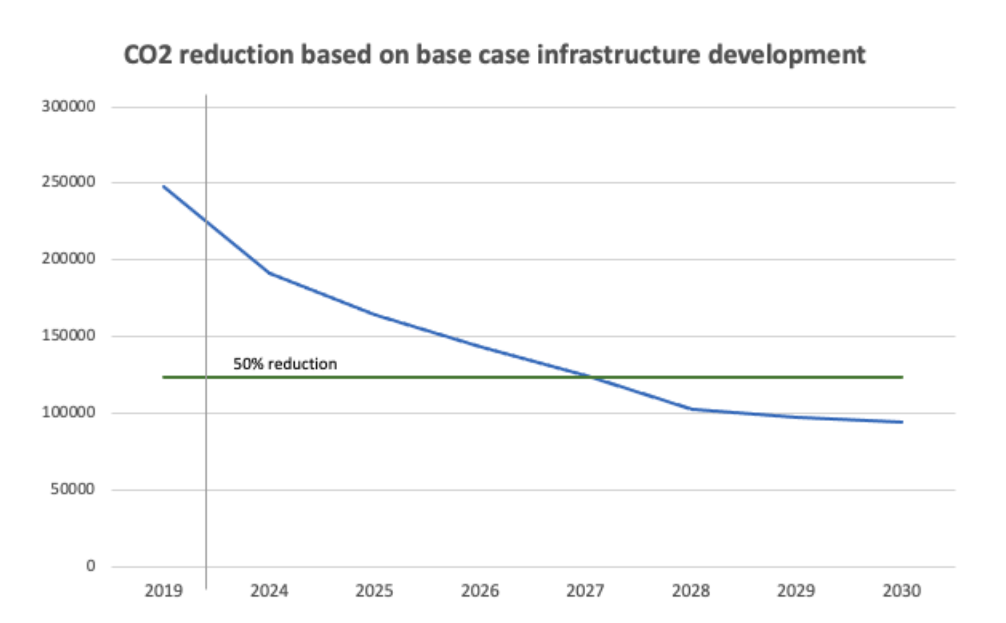


Figure 33.: Emission reduction potential for base-case scenario

Figure 34 gives the distribution of applied voyage conditions [1] for zero-emission voyages in 2024 and 2030.

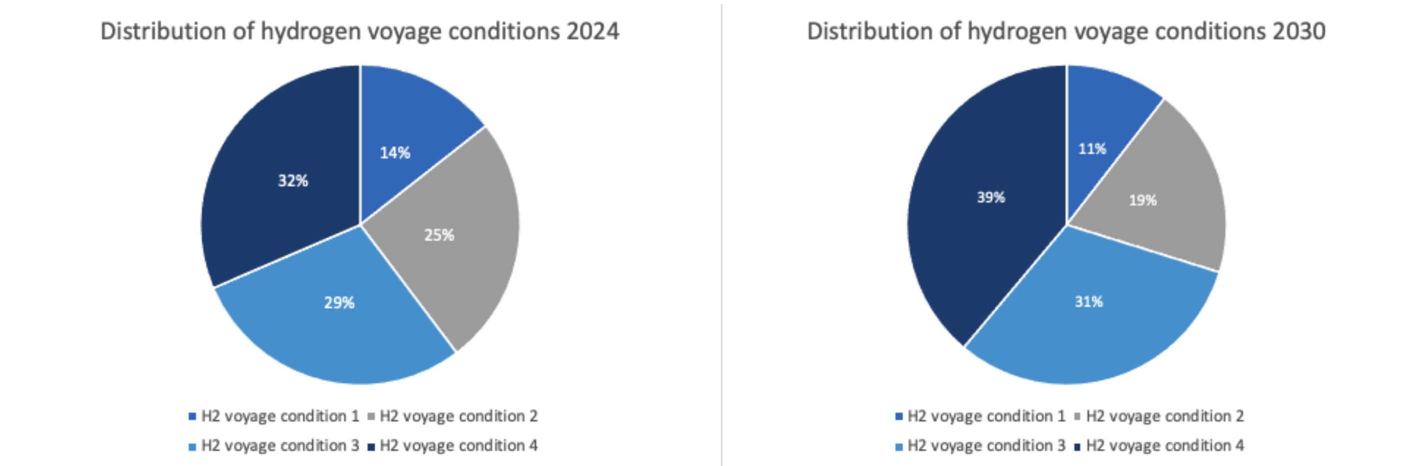


Figure 34.: Distribution of hydrogen voyage conditions for base-case scenario

In 2024, 32% of the voyages can be performed based on condition 4 meaning that most of the zero-emission voyages are possible due to refuelling. The fewest zero-emission voyages can be performed due to hydrogen being available at the destination port. In 2030, as much as 70% of the zero-emission voyages are possible due to condition 3 and 4. If condition 3 was not an option, the emissions would be reduced by 58% in 2030. This gives a difference equal to 4% compared to condition 3 being included. This happens because refuelling is a possibility for many of the same voyages that originally were performed due to fuel supply. The model runs through the conditions one

[1] Condition 1: fuel at the destination port, condition 2: range large enough to reach next hydrogen port, condition 3: fuel supply, condition 4: refuelling on the way

by one. If one condition makes it possible for a zero-emission voyage, the model will not check if one of the other conditions might also be an option.

8.2. Impact assessment low availability scenario

The low availability scenario is developed to give a pessimistic version of the future. Running an IA using the model described in chapter 6 for the low availability scenario as described in section 7.3.2 gives the results in figure 35.

Year	CO2 emission [MT]	Reduction [%]	nr. Of H2 ports	Nr of H2 voyages	H2 voyage condition 1	H2 voyage condition 2	H2 voyage condition 4
2019	247926	0		0			
2024	237513	4%	10	1199	148	307	744
2025	227126	8%	12	2362	188	430	1744
2026	208879	16%	16	4443	738	1294	2411
2027	175708	29%	18	7973	1008	1819	5146
2028	148939	40%	20	11257	1202	2220	7835
2029	131209	47%	20	13532	1611	2924	8997
2030	109074	56%	20	15241	1797	3289	10155
only 12.5% of H2 prpduced available for the fleet							
2030	171579	31%	20	8229	1032	1915	5282

Figure 35.: Results from IA of low availability scenario

The graph in figure 36 illustrates the emission reduction from 2019 to 2030. The graph illustrates that even for a pessimistic version of the future infrastructure development, the domestic fleet will be able to reduce its emissions by 50% within 2030.

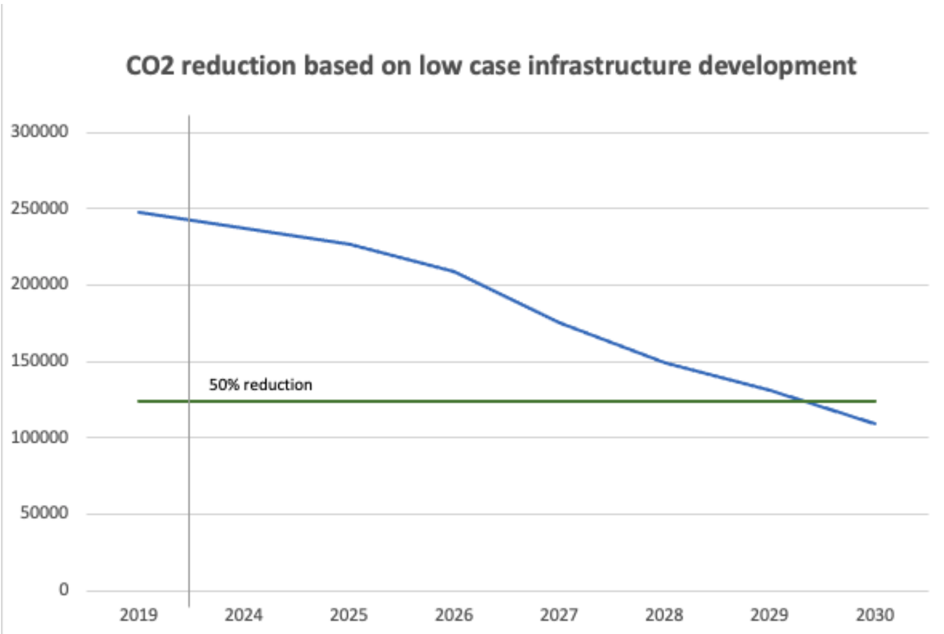


Figure 36.: Emission reduction potential for low availability scenario

In the low availability scenario, fuel supply is not an option. However, a deviation from the original route for refuelling is accepted if the range allows it. Figure 37 gives the distribution for how many of the hydrogen voyages which are possible based on each condition in 2024 and 2030.

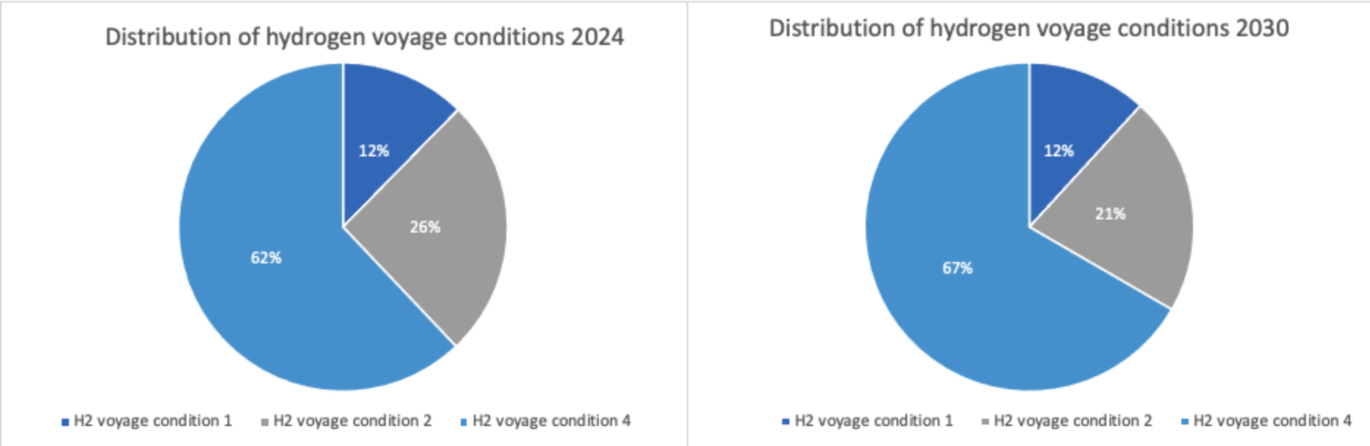


Figure 37.: Distribution of hydrogen voyage conditions for low availability scenario

As figure 37 shows, more than 60% of the voyages can be performed based on condition 4 with refuelling. A large part of the results relies on refuelling being a profitable alternative. If refuelling was not an option, only 5086 voyages would in 2030 be performed using zero-emission fuels. From the number in 2026 in figure 35, this would give an emission reduction equal to about 16% depending on the length of the voyages able to run on hydrogen.

For an even more pessimistic view where only 12.5% of the originally produced hydrogen given in figure 28 would be available for the domestic fleet, the emission in 2030 would only be reduced by 31%.

8.3. Impact assessment high availability scenario

The high availability scenario is developed to give an optimistic version of the future hydrogen availability. Running an IA using the scenario described in section 7.3.3 gives the results shown in the table in figure 38.

Year	CO2 emission [MT]	Reduction [%]	Fuel supply radius [nm]	Nr of H2 voyages	H2 voyage condition 1	H2 voyage condition 2	H2 voyage condition 3	H2 voyage condition 4
2019	247926	0		0				
2024	141700	43%	36	13749	1243	2220	7648	2638
2025	99098	60%	36	19195	1622	2966	10846	3761
2026	76387	69%	36	22228	1869	3440	12591	4328
2027	71724	71%	36	23685	2122	3979	13721	3863
2028	67489	73%	36	25750	2376	4480	16047	2847
2029	65969	73%	36	26315	2409	4563	16661	2682
2030	64726	74%	36	26789	2438	4630	17191	2530
no volume limitation								
2030	60762	75%	36	27855	2932	5623	17150	2150

Figure 38.: Results from IA of high availability scenario

The graph in figure 39 shows the emission reduction towards 2030. The high availability scenario has the same amount and location of ports as in the base-case scenario. However, each port has a larger hydrogen availability. As the graph illustrates, with higher available volume, the fleet can reach a 50% emission reduction by 2025. Comparing this graph to the same graph for the base-case and low availability scenario, one can see that the emission reduction converges in 2027.

In figure 38, the last row shows the result for an infinite amount of available volume for the 20 ports used in this thesis. Assuming a balanced market where each port can deliver the amount of hydrogen demanded by the fleet and that the conditions presented in chapter 5 apply, the fleet can reduce its emissions by 75% by 2030. If the emissions shall be further reduced, more ports must be developed, or the vessel range must increase significantly.

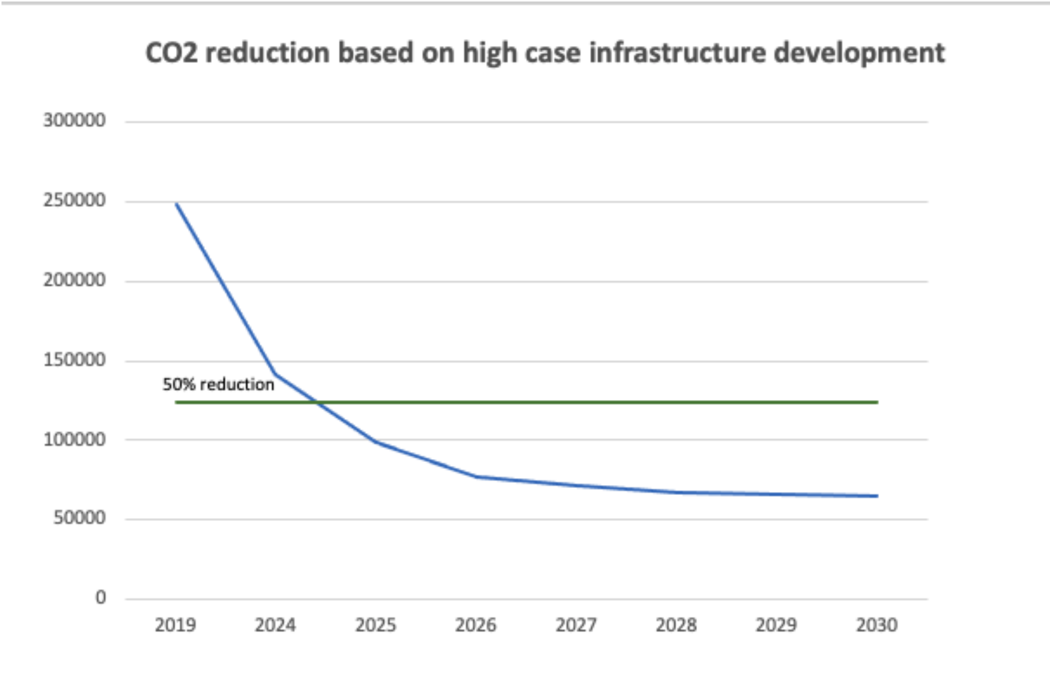


Figure 39.: Emission reduction potential for high availability scenario

As for the base-case scenario, a large part of the hydrogen voyages can be performed due to condition 3 and 4 for the high availability scenario, see figure 40.

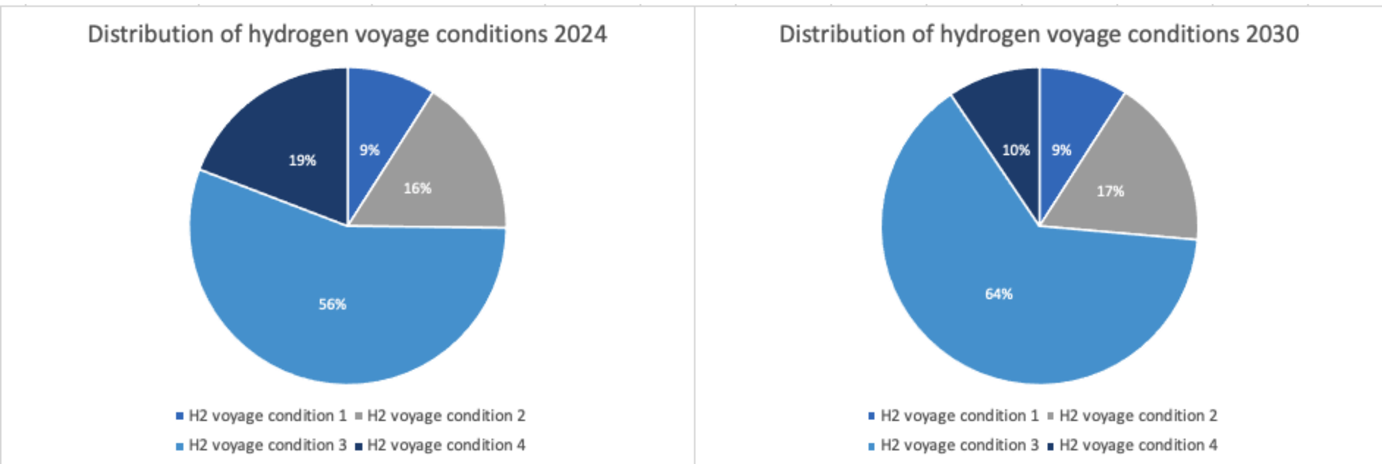


Figure 40.: Distribution of hydrogen voyage conditions for high availability scenario

9. Evaluation and discussion

The results in chapter 8 show that there is a possibility for using hydrogen as fuel in domestic shipping. For all scenarios, the fleet is able to reach a 50% reduction in emissions by 2030. This indicates that based on the availability of hydrogen, the government's goal for emission reduction is reachable.

This chapter will discuss the uncertainties related to the results achieved, and the model created in this thesis.

9.1. Assumptions related to condition 3 - fuel supply

In condition 3 the model checks if there is a possibility that one port which does not have hydrogen available can be reached by a fuel supply barge. It has been assumed that the range of the fuel supply barge would be low, so that using the shortest path will give a sufficiently accurate result for the transport distance. If the profitable fuel supply range becomes large, using the shortest path to calculate fuel supply distance can give a significant margin of error. For example, the shortest distance between two ports in two different fjords can be short while the actual sailing distance is much larger. For the high availability scenario, the fuel supply range is assumed to be 36 nm. This distance is large enough to give a significant deviation in the result. However, due to the location and distribution of ports used in this thesis, and that for many of the same cases condition 3 is an option so is condition 4, the error margin can be assumed negligible. If one is to analyse a different distribution of hydrogen ports the effect might be different. Therefore, ideally, the sea distance should be used in the fuel supply condition.

Fuel supply is only modelled based on the use of a fuel barge. Related to fuel supply both the use of fuel barge and truck is an option. For shorter distances transporting less volume, trucks will most likely also be used. The volume cost of truck transport is larger than for a fuel barge. However, in many cases due to for example fjords, the road distance will be significantly shorter so that the total transport cost for a truck is equal to or less than the fuel barge. Since the model only uses the cost to define the fuel supply range, one can assume that truck transport is included. In many of the cases where the use of shortest path for fuel barge has a large margin of error due to sea distance, the use of truck can be profitable as the road distance is shorter. Assuming that trucks are included as an option will reduce the error margin mentioned in the paragraph above.

The model looks at one voyage at a time. For fuel supply, the model only moves the amount needed to refuel one vessel each time fuel supply is used. In many cases, multiple vessels might need hydrogen in the same port at about the same time. A larger amount of fuel will therefore be transported from the storage at a time than what the model accounts for. With the dynamic storage, this might lead to periods with lower storage levels than what is modelled. Should the result be used for closer analysis of storage capacity, the model should include the effect of transporting multiple refuelling volumes at a time.

In the fuel supply condition, a port that originally does not offer hydrogen can deliver hydrogen. A prerequisite for this to be possible is that the port must be approved for this operation. Refuelling using container swap requires fewer systems and approval than cascade filling. Container swap requires a crane onboard the vessel. Most of the vessels in the fleet selection are self-unloading and will therefore have such a crane onboard. Cascade filling requires more systems onshore and therefore more approval for the port.

9.2. Assumptions related to condition 4 - refuelling

In condition 4 the model checks if the vessel can refuel on the way to the destination port. The cost of refuelling the vessels are not considered. To account for the additional cost of refuelling, the additional sailing distance is needed. As described in section 6.5 due to time consumption the actual distance between two ports was for many cases not calculated. Instead, the shortest path distance was calculated. The shortest path distance can have a large deviation from the actual distance which can give a large deviation in the estimated additional cost. Due to the distribution of hydrogen ports in this thesis, see figure 29, the route deviation will in most cases be small and therefore give a small additional cost. The deviation in results due to costs not being included has therefore, for this thesis, been assumed negligible. However, if the distribution of ports is significantly changed, this limitation in the model can give some deviation in the potential emission reduction.

9.3. Limitations to production and storage modelling

The amount of hydrogen available for the fleet depends on the demand for compressed hydrogen in other industries. If the demand is large in other industries the volume available for the domestic fleet might decrease. If the demand for hydrogen increases, scaling the production of local compressed hydrogen is relatively easy as the production system is modular. A larger uncertainty is the port storage capacity which is not accounted for in this thesis. The storage is only updated when a vessel arrives. The hydrogen produced since the last vessel arrived is then added to the storage. If the time between when each storage is used is large, the storage might exceed its capacity. With a slow production rate, the port might not be able to deliver the amount of hydrogen the model accounts for. However, most of the ports in the model are used quite often so the error margin from this factor should be relatively small.

The model runs through the voyages in chronological order. The dynamic storage is updated for each voyage. If the past ten times the storage in a hydrogen port is updated has been due to condition 3 or 4, the next voyage which ends in the hydrogen port might not be possible with hydrogen fuel due to low storage value. As figure 16 shows there is an "or" gate going from the conditions. If any of the conditions apply for a voyage, the model will not check the other conditions. The storage in the suitable hydrogen port will then be used. Even though multiple conditions might be relevant. For example, if a short voyage goes to a hydrogen port, the vessel range might be large enough to reach the next hydrogen port as well. The vessel would in reality most likely refuel in the next hydrogen port. For the model used in this thesis, the vessel will refuel a full tank in both ports leading to higher consumption than what actually would be. The model does not look for the optimal distribution of conditions, it looks at one condition at a time for each voyage isolated. For a more detailed analysis of fuelling conditions, a global view of the fleet must be implemented.

9.4. Limitations to system boundaries

The model in this thesis uses a historical operational pattern from 2019 and assumes that this stays the same as the fleet transfers towards a zero-emission fleet. However, in this process, an optimisation of the fleet's operational pattern will most likely to some extent happen as in the HeidelbergCement and Felleskjøpet case described at the beginning of this thesis. To increase capacity utilisation of the vessels, reduce cost, and energy consumption, a collaboration between companies and improved planning will most likely take place. The effect of an optimised fleet will lead to the result achieved in this thesis probably being too pessimistic.

The effect of fleet development is not included in this thesis. It assumes that if the infrastructure exists, so will the needed hydrogen-fuelled vessels. However, designing and building vessels takes time. As mentioned in the introduction to this thesis, if the domestic fleet should reduce its emissions by 50% by 2030, 700 low- and 400 zero-emission vessels must be built. The domestic bulk fleet under consideration in this thesis consists of 146 vessels. To keep up with the infrastructure development around seven new bulk vessels able to run on hydrogen must be built each year until 2030. The first hydrogen-fuelled vessels are not expected to be in operation before 2023/2024. It is unlikely that the fleet development will be large enough to support the emission reduction based on hydrogen availability presented in chapter 8.

This thesis only looks at a part of the domestic fleet. It does not analyse the entire Norwegian domestic fleet's emission reduction potential, only the fleet selection described in chapter 2. Due to different operational patterns for different fleet selections, the result in this thesis might not be representative for other parts of the domestic fleet. However, the vessels operating along the Norwegian coast generally have low transport distances. Hydrogen will therefore, in many cases, be relevant as long as the speed demand is not significantly larger.

9.5. General remarks

Only the operational emissions are included in this thesis. As figure 2 in chapter 2 shows, the value chain for hydrogen consists of more than just the operational emissions. Producing and storing hydrogen demands energy. Depending on the energy mix used for production and the transportation method, the LCE might not change that much. Figure 6 in section 3.2.1 shows that with today's energy mix, production of hydrogen using electrolysis has almost the same emissions as SMR without CCS. To reduce global emissions, it is important to look at the LCE of green fuels.

Since many of the same voyages can be performed due to condition 3 and 4 as the last row in figure 32 illustrates, the uncertainty for condition 3 or 4 alone will not have that large effects on the result. Removing both condition 3 and 4 will however give a large deviation from the presented results as more than 60% of the hydrogen voyages can be performed due to these two conditions. It is, however, not likely that neither condition 3 nor 4 will be possible. The largest effects on the results will therefore come from removing hydrogen ports, as the first years of the low availability scenario shows. In addition, reducing available volume will have a large effect as illustrated with the different scenarios. This effect is, however, not as large as removing ports.

As discussed above, the model has some assumptions that lead to a deviation from reality in the results. However, some of the assumptions lead to a more optimistic result and some to a more pessimistic result. Some of the assumptions will therefore level each other out. There will still be a deviation as it is hard to predict the future with 100% accuracy. However, with three scenarios a combination of these three should give a good picture. Each scenario gives a result where the fleet is able to reduce its emission by 50% before 2030. Accounting for the margins of error, the result achieved still shows that the infrastructure development will probably not the bottleneck for emission reduction in the Norwegian bulk fleet selection analysed in this thesis.

10. Conclusion

The aim of this thesis was to perform a scenario-based IA of how the development of infrastructure for compressed hydrogen affects the domestic bulk fleet in Norway's potential for emission reduction. The background for this analysis was the Norwegian government's target of 50% emission reduction for the domestic fleet by 2030. A selection of the domestic fleet in Norway has been under consideration in this thesis. This selection has an average age of 28 years and is therefore in need of a replacement. The part of the bulk fleet that operates at least 15% of its time in Norway has been used in the thesis. The model created is based on a historical operational pattern for the selected fleet retrieved from AIS data.

The result from the analysis shows that infrastructure development is probably not the bottleneck for the domestic bulk fleet in Norway's emission reduction potential. Even for the pessimistic scenario, the fleet is able to reach the government's goal of 50% emission reduction by 2030. For the base-case scenario - the most likely scenario - the fleet will reach a 50% reduction by 2028. In 2030, the fleet will be able to reduce its emissions by 62% based on fuel availability. Only looking at the location of ports, and assuming that each port has an infinite amount of hydrogen available, the fleet has an emission reduction potential equal to 75% in 2030. To reach 100% emission reduction, the vessel range must increase significantly or more ports with hydrogen available must be developed.

Looking at the distribution of hydrogen voyage conditions, one can see that the results presented highly depends on the strength of the assumptions related to refuelling and fuel supply. The result of the low availability scenario show the importance of the input data for hydrogen port location.

The hydrogen availability seems to be sufficient to reach the government's emission reduction goal. The fleet development, on the other hand, will most likely have trouble following this development. The first vessels are not planned to be in operation before 2023/2024. If the fleet development is to be sufficient to achieve the desired emission reduction, the number of newbuilding projects must increase significantly.

The use of a quantitative model together with a scenario analysis seems to be a sufficient tool to gain insight into possible emission reduction in a fleet based on fuel availability development. Combined the different scenarios provide a better understanding of how the fleet is affected by fuel availability, and which parameters that have the largest effect on the result.

11. Recommendations for future work

Below follows suggestions for future work to improve the model and get better insight into the fleet's emission reduction potential:

- Develop a more efficient and reliable method to calculate the distance between ports in order to implement cost limitations for refuelling and reduce the margin of error for fuel supply.
- The fuel flow in the current model is exclusively dependent on time - first come first served. A global view should be implemented for a more optimal choice of fuel flow.
- Looking at the difference between the three scenarios' volume availability, it is important to improve the accuracy of the assumption related to how much of the produced hydrogen will be available for the selected fleet. Therefore, better research on the amount of hydrogen that will be available for the domestic fleet should be performed.
- The entire fleet will most likely not run on the same fuel. Therefore, the model should be extended to include multiple zero- or low-emission fuels.
- It seems that the infrastructure development is not the bottleneck for the fleet's zero-emission potential. The challenge towards 2030 will be building enough vessels able to run on hydrogen. Therefore, an analysis that includes the limitation in vessel production and therefore vessel availability should be performed to get a better insight into the fleet's actual emission reduction potential.

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A. Transport cost for fuel supply

Source: Aasheim, D., Aamot, E. and Karlsrud, C. *Price development of Grey, Blue and Green Hydrogen and Ammonia 2020-2030*(2020)

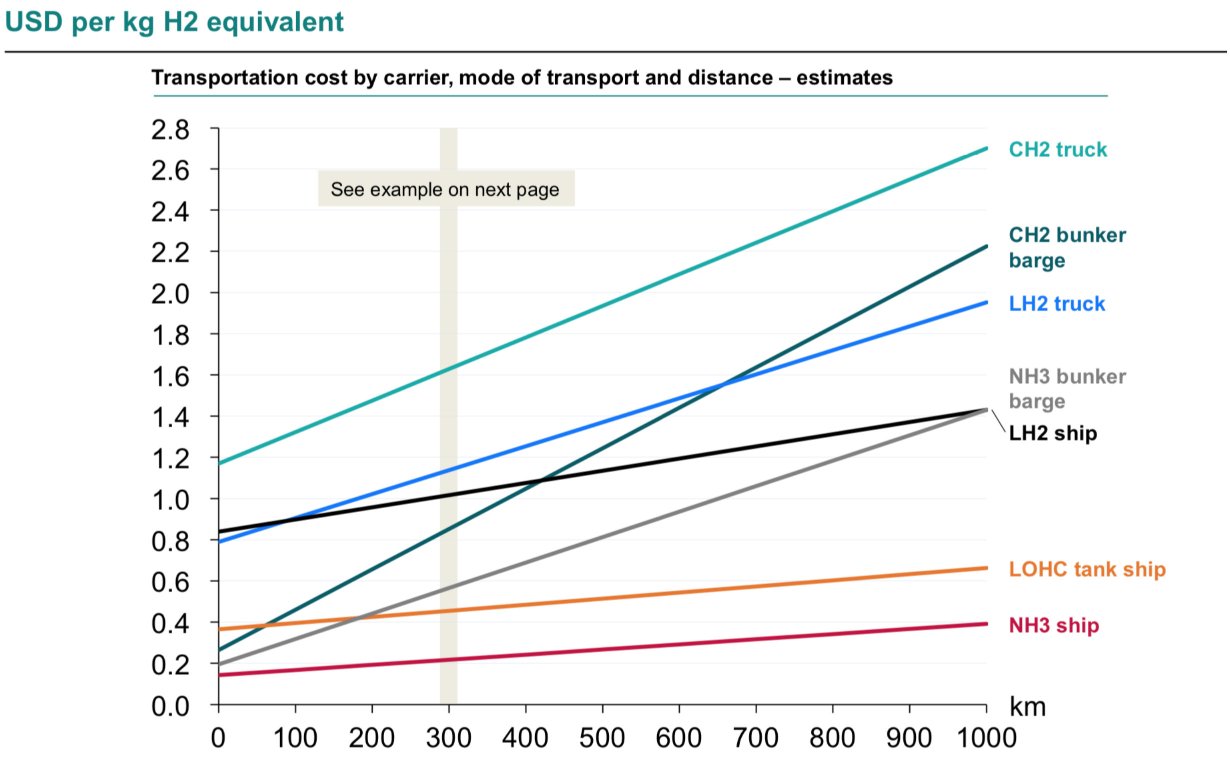

Figure 41.: Transportation cost of hydrogen

The graph shows that the initial cost of fuel supply is about 0.3 USD. Further the cost increases linearly. The cost of fuel supply using barge is based on the graph 2.5 NOK/kg + 0.03 NOK/(kg*nm) per kg H2 equivalent.

B. Hydrogen fuel cost

The graph below is based on research done by Green Shipping Programme (GSP) 2021. Only lines relevant for hydrogen is taken out from the original figure.

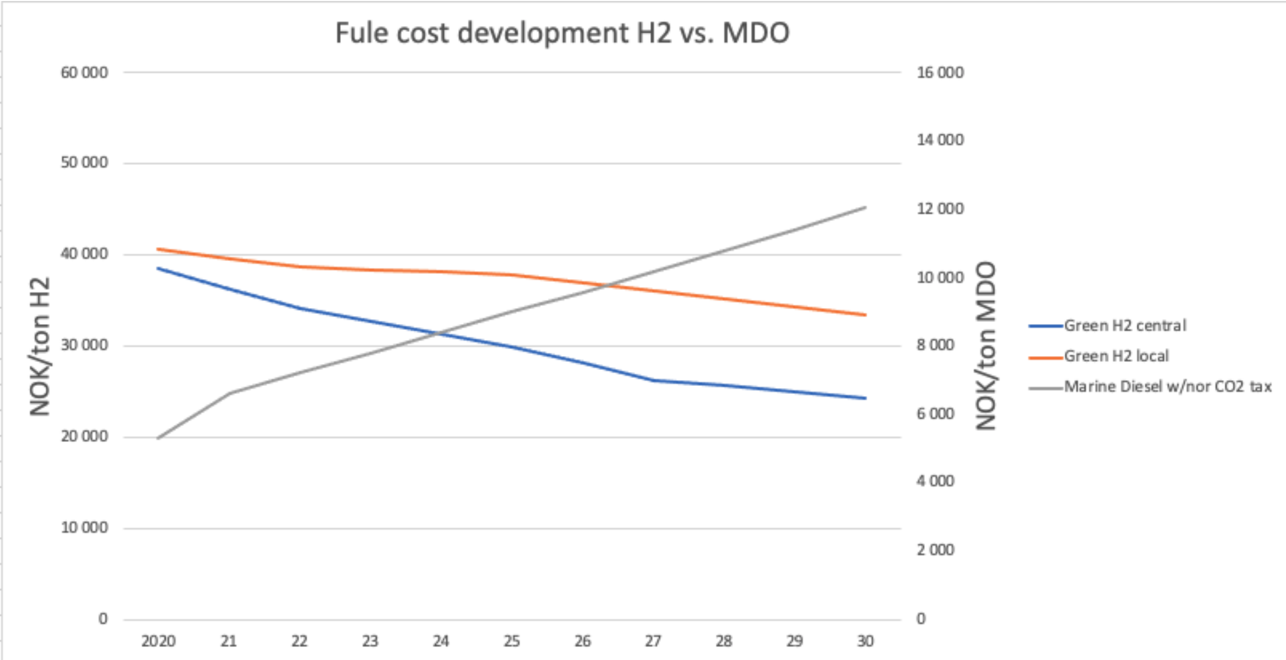

Figure 42.: Fuel cost from GSP

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