Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Anneli Sørland Torper

Greenhouse Gas Reduction Potential in Norwegian Coastal Shipping

A Well-to-Wake Analysis of Alternative Shipping Fuels

Master's thesis in Industrial Ecology
Supervisor: Anders Hammer Strømman
Co-supervisor: Diogo Kramel

June 2023

NTNU
Norwegian University of
Science and Technology

Anneli Sørland Torper

Greenhouse Gas Reduction Potential in Norwegian Coastal Shipping

A Well-to-Wake Analysis of Alternative Shipping Fuels

Master's thesis in Industrial Ecology
Supervisor: Anders Hammer Strømman
Co-supervisor: Diogo Kramel
June 2023

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Thesis description

Well-to-wake assessment of Fuel Options for Coastal Shipping in Norway

As part of the KPN research project CLIMMS (Climate Change Mitigation in the Maritime Sector), NTNU has developed a computational model for the fuel combustion and emissions to air from the global shipping fleet; the MariTEAM model. The model uses historical AIS data (automatic identification system, i.e., ship location) in combination with weather data, and ship technical data. The master thesis will be performed in co-operation with the CLIMMS project and will contribute with expanding the model to enhance the calculation of upstream fuel emissions in Norway.

The objective of this master's thesis is to perform a synthesis study of well-to-wake emissions of selected fuels applied in coastal shipping in Norway. The aim is to calculate the well-to-wake emissions of alternative fuels and investigate the emission reduction potentials of alternative fuel substitution. This study can contribute to a better understanding of how to mitigate domestic shipping emissions in Norway in order to reach Norway's climate goals through the use of alternative fuels.

The following tasks are to be considered:

1. Selection of a suitable set of fuels and fuel pathways to study.
2. Selection of a suitable ship segment to study.
3. Perform a literature review on well-to-tank emissions of selected fuels.
4. Harmonize well-to-tank emissions with parametric analysis.
5. Calculate tank-to-wake emissions for the selected ship segment with the MariTEAM model.
6. Analysis of the climate implications of fuel substitution.

Supervisor: Professor Anders Hammer Strømman
Co-supervisor: PhD Candidate Diogo Kramel

Abstract

Climate change necessitates reducing greenhouse gas emissions across all sectors, including shipping. One proposed solution for reducing shipping emissions is the adoption of low-emission fuels. This thesis investigates the potential for reducing greenhouse gas emissions by substituting conventional fuels with low-carbon alternatives applicable to coastal shipping in Norway. Specifically, LNG, hydrogen, and ammonia are assessed as alternative shipping fuels for the Coastal Express ship segment.

A comprehensive well-to-wake analysis of low-carbon fuel alternatives has been developed to determine which fuel option results in the lowest greenhouse emissions for the Coastal Express. Tank-to-wake emissions are calculated using the MariTEAM model, a comprehensive bottom-up approach that estimates emissions based on ship-operational conditions. Well-to-tank emissions for alternative fuels are assessed through a parametric analysis based on existing fuel studies.

The results indicate greenhouse gas emissions reduction potential with all assessed alternative fuels. Hydrogen demonstrates the lowest tank-to-wake emissions, followed by ammonia. LNG exhibits the highest tank-to-wake emissions among the three alternatives but can still achieve a 25 % reduction compared to conventional fuels. When considering well-to-tank emissions, the fuel production method heavily influences the reduction potentials. Green hydrogen produced via electrolysis offers the lowest well-to-wake greenhouse gas emissions, followed by hydrogen produced from natural gas. Ammonia shows significant potential for emissions reduction but requires renewable energy in the synthesis process and green hydrogen as feedstock to meet the reduction targets.

Due to its mature technology and availability, LNG can serve as a short-term conventional fuel substitute. However, it is insufficient to meet the emission reduction targets set for the shipping sector. Both hydrogen and ammonia have the potential to serve as conventional fuel substitutes and effectively reduce shipping emissions in line with emission targets. Nevertheless, limited availability, high costs, and technological immaturity pose challenges to widespread adoption. The Coastal Express, positioned uniquely in Norwegian coastal shipping, can address these challenges and make significant strides towards achieving a zero-emission shipping sector.

Sammendrag

Klimaendringer gjør det nødvendig å redusere klimagassutslipp i alle sektorer, også innen skipsfart. En foreslått løsning for å redusere utslippene er å erstatte dagens fossile drivstoff med lav- eller nullutslipps-alternativer. I denne oppgaven undersøkes potensialet for å redusere klimagassutslippene til Kystruten ved å erstatte fossile drivstoff med LNG, hydrogen eller ammoniakk.

I denne oppgaven er det utviklet en omfattende vugge-til-grav (well-to-wake) analyse av drivstoffalternativene for å determinere hvilket alternativ som gir lavest klimagassutslipp. Direkte utslipp fra forbrenning av drivstoff (tank-to-wake) beregnes ved hjelp av MariTEAM-modellen, en omfattende "bottom-up" modell som estimerer utslipp basert på skipets driftsforhold. Utslippene knyttet til produksjon av drivstoff (well-to-tank) er estimert ved hjelp av en parametrisk analyse basert på tilgjenglige studier av de alternative drivstoffene.

Resultatene viser at det er potensial for utslippsreduksjon med alle de vurderte alternative drivstoffene. Hydrogen har de laveste utslippene tank-to-wake, etterfulgt av ammoniakk. LNG har de høyeste utslippene av de tre alternativene, men kan likevel oppnå en reduksjon på 25% sammenlignet med fossile drivstoff. Når det gjelder utslipp gjennom hele livsløpet (well-to-wake), er reduksjonspotensialet i stor grad avhengig av produksjonsmetode. Grønt hydrogen produsert ved hjelp av elektrolyse gir de laveste utslippene, etterfulgt av hydrogen produsert fra naturgass med og uten integrert karbonfangst. Ammoniakk som drivstoff har et betydelig potensial for å redusere utslippene, men det kreves fornybar energi i synteseprosessen og grønt hydrogen som råstoff for at reduksjonen skal være tilstrekkelig for å nå klimamålene.

På grunn av modenhet og tilgjengelighet kan LNG erstatte konvensjonelle drivstoff på kort sikt. LNG reduserer imidlertid ikke utslippene nok til at drivstoffbytte alene kan føre til at klimamålene nås. Både hydrogen og ammoniakk har potensial til å erstatte konvensjonelt drivstoff og redusere utslippene fra skipsfarten i tråd med klimamålene. Begrenset tilgjengelighet, høye kostnader og teknologisk umodenhet gjør imidlertid at hydrogen og ammoniakk ikke er gode drivstoffalternativer per i dag. Kystruten har en unik posisjon i norsk kystfart og kan være en viktig bidragsyter for at hydrogen og ammoniakk blir tilgjengelig som drivstoff langs kysten i Norge.

Preface

This thesis is the conclusion of my master's degree in Industrial Ecology at the Norwegian University of Science and Technology (NTNU) in Trondheim. The thesis is a continuation of my project work and amounts to 30 credits.

Two years ago I wrote my bachelor's thesis about hydrogen production and demand in Norway. While working on that thesis I had meetings with several people with different opinions on whether hydrogen was a suitable fuel for shipping or not. Both LNG and ammonia were mentioned as better alternatives. In this thesis, I am able to conclude on my own what fuel offers the best possibility for reaching our climate goals.

I want to express my gratitude towards my supervisor, Professor Anders Hammer Strømman, for providing helpful guidance and constructive feedback throughout this year. I want to thank my co-supervisor, PhD Candidate Diogo Kramel, for helping me with the MariTEAM model and providing useful insight on alternative fuels and shipping emissions. Furthermore, I want to thank my friends, family, and fellow students for their support, good discussions, and much-needed breaks these two years. Last, but definitely not least, I want to thank Erlend Øien, my significant other, for being my Python mentor, personal chef, and mental support throughout this year. This thesis would not be what it is without you. We made it!

Trondheim, 14th of June 2023

Anneli Sørland Torpe

Contents

List of Figures

List of Tables

Acronyms

AIS Automatic Identification System.

ASU Air Separation Unit.

ATR Autothermal Reforming.

CCS Carbon Capture and Storage.

CH_4 Methane.

CO Carbon Monoxide.

CO_2 Carbon Dioxide.

CO_2eq Carbon Dioxide Equivalents.

DNV Det Norske Veritas.

dwt Deadweight Tonnage.

EF Emission Factors.

EU European Union.

FC Content of carbon or sulphur present in fuel.

GHG Greenhouse Gas.

GJ Gigajoule.

GWP Global Warming Potential.

H_2 Hydrogen.

H_2O Water.

HFO Heavy Fuel Oil.

IMO International Maritime Organization.

IPCC Intergovernal Panel on Climate Change.

LCA Life Cycle Assessment.

LF Engine load as a percentage of maximum continuous rating.

LNG Liquefied Natural Gas.

MGO Marine Gas Oil.

MJ Megajoule.

MMSI Maritime Mobile Service Identity.

N_2O Nitrous Oxide.

NH_3 Ammonia.

NO_x Nitrogen Oxides.

OC Organic Carbon.

PEM Proton Exchange Membrane.

PM Particulate Matter.

SFOC Specific Fuel Consumption.

SMR Steam Methane Reforming.

SO$_x$ Sulphur Oxides.

TTW Tank-to-wake.

UN United Nations.

WTT Well-to-tank.

WTW Well-to-wake.

1 Introduction

This master thesis aims to expand knowledge of greenhouse gas emission reduction potentials with maritime fuel substitutes. In this section, the background and motivation for substituting conventional fuels with low-carbon alternatives are first presented. Then, a presentation of the state of knowledge including climate forces in the shipping sector, well-to-wake emission modeling, and alternative shipping fuels follows. Finally, the research objective and report structure are presented. This thesis is a continuation of a preliminary project work conducted in the fall semester of 2022. The introduction will have similarities with the project work. This applies to the background and motivation and well-to-wake modeling, in particular [1].

1.1 Background and motivation

Climate change is an ongoing threat to human well-being and planetary health, and mitigation requires effort in many different sectors. Continued Greenhouse Gas (GHG) emissions will lead to increasing global warming, and reducing the emissions is crucial for climate change mitigation. The actions implemented today will impact the climate and mankind for thousands of years. [2]

The shipping sector is responsible for about 3 % of global anthropogenic greenhouse gas emissions, and the emissions are expected to increase in the years to come [3]. Increasing demand for maritime transportation will require more efficient emission-reducing measures [4]. The main source of emissions in the shipping sector is the exhaust gas from fuel combustion, followed by fuel production [5]. Substituting conventional emission-intensive fossil fuels with low-emission fuel alternatives is therefore crucial for reducing greenhouse gas emissions in this sector [6].

The Paris Agreement, a legally binding international treaty on climate change, was signed by 196 countries at the United Nations (UN) Climate Change Conference in France in December 2015 and put into force one year later. The treaty claims action to "hold the increase in global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels[...]". [7] The International Maritime Organization (IMO), a specialized UN agency with responsibility for the prevention of marine and atmospheric pollution by ships [8], published in 2018 a strategy on climate change mitigation in the shipping sector, based on the Paris Agreement content. The strategy forces 50 % climate emission reductions by 2050 (compared to 2008) and envisions zero emissions within this century. The strategy was adopted by the IMO member countries who agreed to a deal pursuing the emission reduction ambitions. [9]

Norway's commitment to the Paris Agreement and the IMO agreement pursue rapid and extensive GHG emission reductions in domestic shipping [10]. In addition to the international treaties, the Norwegian government has implemented 24 national climate and environmental goals. One of them is to be a low-emission society by 2050. In 2030, Norway is going to be climate neutral, and greenhouse gas emissions shall be reduced by 55 % (compared to the level of greenhouse gas emissions in 1990). Climate neutrality can be achieved, i.a., through emissions trading systems. [11] The shipping industry is going to be implemented in the European Union (EU) Emissions Trading System (EU ETS) by January 1st, 2024, and will consequently be implemented in Norway when the adapted regulations are ready. The Emissions Trading System establishes a limit on the total amount of greenhouse gas emissions permitted in the sector, and emission permits are distributed via a quota system. The aim is to reduce emissions gradually by decreasing the amount of quotas. [12]

Every year, a barometer on the transition towards a more environment-friendly shipping sector is published by Det Norske Veritas (DNV), on behalf of the Norwegian Ministry of Climate and Environment. The 2022 barometer revealed a very slow transition. The greenhouse gas emissions are 20 % higher than what they should be at this point in order to reach the emission targets. [13]

Emissions from domestic shipping[1] and fisheries are estimated to be 3.7 million Carbon Dioxide Equivalents (CO_2eq) in 2021 according to Statistics Norway (SSB) [14]. This is an increase of 25 % since 2017 [10].

1.2 State of the art

This section provides the state-of-the-art on climate forces in the shipping sector, alternative shipping fuel substitutes, and well-to-wake emission modeling.

1.2.1 Climate forces in the shipping sector

Fuel-related emissions in the shipping sector can be divided into indirect and direct emissions. Indirect emissions occur in the fuel production stage, while direct emissions are mainly caused by fuel combustion and depend on the properties of the shipping fuel and the configuration of the engine. Carbon Dioxide (CO_2), Water (H_2O), and Nitrogen Oxides (NO_x) emissions are directly linked to the hydrocarbon structure and presence of non-hydrocarbon components in the fuel, while other emissions are caused by non-ideal combustion circumstances. Carbon Monoxide (CO) and Particulate Matter (PM) emissions are caused by incomplete combustion of fuels and unburned fuels and Organic Carbon (OC) emissions are caused by combustion lubrication oil. NO_x and hydrocarbon (e.g., Methane (CH_4)) emissions are related to the temperature conditions in the engine. [4]

These emissions species have different impacts on the climate. The three greenhouse gases, CO_2, Nitrous Oxide (N_2O), and CH_4, work as the glass walls of a greenhouse. The gases create a barrier in the atmosphere, restraining solar radiation from leaving the atmosphere. Increased concentration of greenhouse gases in the atmosphere results in a reduction of solar radiation passing through the barrier, which causes temperature rise on the earth's surface. [15] Other emission species, e.g., Sulphur Oxides (SO_x) and NO_x, will cause negative radiative forcing and earth surface temperature decrease [16]. Despite neutralizing increased temperature rise, SO_x and NO_x emissions are causing air pollution and are harmful to human health and ecosystems [17, 18]. SO_x and NO_x emission mitigation have therefore been prioritized by authorities [19].

The emissions species are influencing the climate for various amounts of time. CH_4 is a potent short-lived greenhouse gas. It has a greater effect on the global warming potential in a short-term perspective, than in a long-term perspective. NO_x and SO_x emissions will also influence the climate for a shorter amount of time. [20] CO_2 on the other hand, will remain in the atmosphere for hundreds of years without being significantly decomposed [21].

For quantification of the climate impact of the different climate forces, scientists have developed emissions metrics. Emission metrics are tools that allow quantifying and comparison of different emissions species and their impact on the climate over time. The metrics provide a consistent framework for assessing the environmental impact of various gases based on their warming potential and lifetime in the atmosphere. The most known emission metric is *Global Warming Potential* (GWP), which converts the different emission species to CO_2eq based on their influence over a given time horizon. In a 100-year perspective, 1 g of CH_4 equals 28.5 g of CO_2eq, but in a 20-year perspective, the conversion factor is 83.9. [20] Another emission metric is *Global temperature potential* (GTP), which measures the temperature change at the end of the given time period [22].

---

[1] Domestic shipping is defined as shipping between two domestic ports. In Norway, Svalbard and installations on the Norwegian continental shelf is included.

1.2.2 Conventional and alternative fuels for maritime shipping

Today, Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) are the most common fuels applied in maritime shipping. Both HFO and MGO are produced from crude oil. After extraction, crude oil is processed in refineries with MGO and HFO as products. [4] MGO is a lower-sulphur alternative to HFO, but production of the fuel is more energy-intensive [23]. Several alternative low-carbon fuels are relevant for coastal shipping in Norway. Biofuels can take advantage of biological residue and partly or solely replace HFO or MGO in conventional engines, but the environmental benefit depends on residue origin. Batteries enable electrical propulsion, but current technology is not fitted for longer sailing distances. LNG, hydrogen, and ammonia are alternative fuels fitted for longer distances and can reduce GHG emissions significantly. [10]

Liquefied Natural Gas (LNG) has for several years received ascending attention as a promising alternative to conventional fuels, and unlike other fossil fuels, consumption of LNG is expected to continue to grow. Compared to HFO and MGO, combustion of LNG results in no SO_x emissions. [24] Conditioned by engine technology, PM and NO_x emissions will also decrease [5]. Overall, LNG has the potential of reducing GHG emissions with 25 - 30 % in a Tank-to-wake (TTW) perspective [5, 21]. However, when Well-to-tank (WTT) emissions are taken into account, this reduction can be diminished [5]. The WTT emissions will vary based on production place. LNG from the North Sea has, for example, lower global warming potential than LNG from Qatar. [25]

As the term indicates, LNG is made of natural gas. After extraction, natural gas can either be liquefied or compressed in order to be used as fuel. Liquefaction is favorable to compression because of higher energy density, resulting in lower storage demand. [26] LNG is favorable as an alternative shipping fuel for several reasons. First of all, LNG is competitive in price and availability [27]. There is also no need for abatement technologies, as present engines and infrastructure can be used [19]. Studies even indicated that LNG can reduce the maintenance demand. Additionally, LNG also lower the noise level, which is preferable for vessels sailing close to shore and passenger vessels. [27]

Challenges of LNG include pipeline emissions and fuel storage. Pipeline emissions are mainly due to the burning of fossil fuels at the compressor stations and methane leaks. These emissions can be reduced with more energy-effective compressors and stricter maintenance practices. [28]
When it comes to storage, the pressure increases with time, resulting in exceeded quality and safety thresholds. LNG can therefore not be stored for an unlimited amount of time and the technology requirements are strict. [29]

Hydrogen (H_2) and Ammonia (NH_3) are less mature, but promising maritime fuels. Hydrogen can be produced in several ways, but natural gas reforming and electrolysis are currently the most used technologies. With water as the only product of combustion, hydrogen has no GHG emissions tank to wake. The emissions related to fuel production depend solely on how the hydrogen is produced. For practical reasons, hydrogen is "colored" based on how it is produced. If hydrogen production is based on natural gas as a feedstock, the hydrogen is grey, while hydrogen produced with electrolysis is green. If the on-site emissions are captured with Carbon Capture and Storage (CCS) technology, grey hydrogen turns blue. Blue hydrogen is a low-carbon alternative to hydrogen produced with electrolysis. [30]

Ammonia has arisen as an alternative to hydrogen, mostly because the energy density is higher and the energy needed for liquefaction or compression is lower [10]. The majority of ammonia produced today is produced with the Haber-Bosch process [31]. In this ammonia synthesis process, nitrogen and hydrogen are used as feedstock. Because of the hydrogen feedstock, the emissions of ammonia production are highly dependent on how the hydrogen is produced. [31]
For simplicity reasons, ammonia is colored in the same way as hydrogen. Grey ammonia is produced with grey hydrogen as feedstock, while green ammonia is produced with green hydrogen.

The Haber-Bosch process is energy-intensive, with an energy demand of 25 - 30 Gigajoule (GJ) per ton of ammonia [32]. The process is currently one of the largest energy consumers and sources of GHG emissions globally, responsible for 1.2 % of the global anthropogenic CO_2 emissions [33]. If the electricity used for ammonia synthesis is carbon intensive, the WTT emissions of ammonia will be higher than if the electricity origin in renewable energy [32].

Compared to hydrogen, ammonia has a higher volumetric energy density and lower energy demand for liquefaction, causing lower storage emissions and costs [32]. Another important advantage of ammonia is the existing production and infrastructure. This includes pipelines and transport by ship, rail, or road, as around 180 million tons of ammonia are produced and transported annually on a global scale. [25]

As a fuel, ammonia can be used either in combustion engines or indirectly in fuel cells [32]. In combustion engines, the combustion of ammonia will cause nitrogen emissions and water. Only small modifications are most likely needed for the current engines to adjust for ammonia combustion, but for so long, this technology along with ammonia fuel cells are considered immature. [10]

1.2.3 Well-to-wake emissions modeling

Well-to-wake (WTW) models are comprehensive models with the purpose of estimating emissions of maritime fuels through the entire life cycle. The models are also referred to as well-to-propeller and are the maritime equivalent of well-to-wheel assessments used for vehicles. The model includes emissions from every stage of the fuels' life, from extraction (well) to combustion (wake), and are often divided into two individual parts; well-to-tank and tank-to-wake. Well-to-tank emissions include emissions from extraction/cultivation of raw materials, processing and refining, and transport, distribution, and storage, while tank-to-wake emissions include emissions from the combustion of the fuel. [34] The well-to-wake model structure is visualized in figure 1.

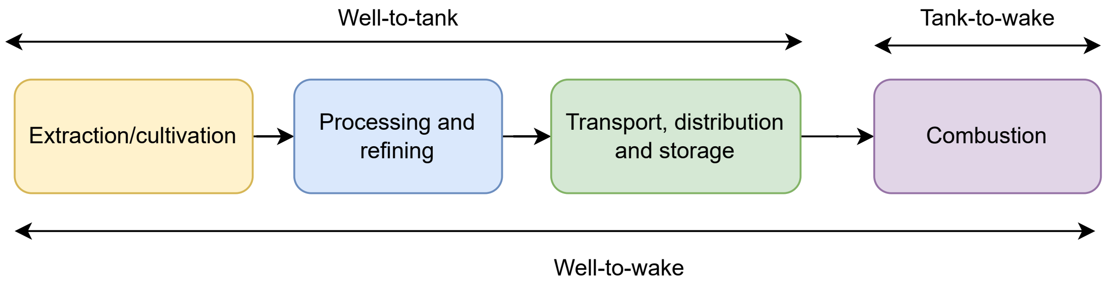


Figure 1: Components in well-to-wake emission modeling. Well-to-tank includes extraction/cultivation of raw materials, processing and refining, and transport, distribution and storage. Tank-to-wake includes combustion of the fuel.

Several well-to-wake model approaches have been developed in order to estimate emissions in the shipping sector. In general, the approaches can be separated into two categories; top-down and bottom-up approaches. Top-down approaches are based on fuel sales, while bottom-up approaches are based on actual fuel consumption. The different model approaches can result in significant differences in estimated well-to-wake emissions. For international shipping, estimated CO_2eq annually varies between 700 million tons and 1300 million tons. Many experts hold the view that top-down methods have a tendency to undervalue emissions since they are based on the amount of fuel purchased. [4]

Statistics Norway (Statistisk sentralbyrå) uses a top-down approach for the official shipping emissions statistics in Norway. The GHG emission estimation of 2.95 million tons CO_2eq in 2017 for domestic shipping is based on fuel sales and is not taking fuel bunkered up abroad into account. On contract research for the Norwegian Coastal Administration (Kystverket), DNV has created a bottom-up approach for national maritime emissions in Norway. The model is based on Automatic Identification System (AIS) data combined with vessel databases. With this approach, domestic shipping was estimated to emit 4.8 million tons of CO_2eq in 2017, which is a 60 % higher estimate than the national statistics. Another interesting discovery is that the bottom-up approach indicates an increase in domestic shipping emissions between 2012 and 2017, while the national statistics indicate a decrease in the same period of time. [10]

A bottom-up approach is also applied in the IMO GHG study, in the STEAM model (**S**hip **T**raffic **E**mission **A**ssessment **M**odel), and in the MariTEAM model (**M**aritime **T**ransport **E**nvironmental **A**ssessment **M**odel). These comprehensive approaches are combining ship technical data and position data to estimate well-to-wake emissions but with some variations in the inventories. Both MariTEAM and STEAM use AIS data for the identification of ships and their geographical locations. [3, 4, 35]

1.3 Research objective and thesis structure

Norway is committed to reducing greenhouse gas emissions in the shipping industry through international treaties. Since fuel is the primary source of greenhouse gas emissions, substituting conventional fuels with low-carbon alternatives is a potential solution for meeting the reduction targets. The objective of this thesis is to study greenhouse gas emission reduction potentials by substituting conventional fuels with low-carbon alternatives that potentially can be applied in coastal shipping in Norway. The thesis evaluates the viability of using LNG, hydrogen, and ammonia as low-carbon fuel alternatives, with the Norwegian Coastal Express serving as the representative ship segment for coastal shipping.

Greenhouse gases are emitted through the entire life cycle of a fuel. This thesis offers a complete well-to-wake analysis of the alternative fuels, from the extraction of raw materials to combustion in the ship engines. The tank-to-wake emissions are estimated with the comprehensive MariTEAM model, while a parametric analysis based on present fuel studies enhances the model with well-to-tank emissions related to fuel consumption in Norway.

The research question of this thesis is formulated as follows:

Can LNG, hydrogen, or ammonia substitute conventional fuels and reduce the greenhouse gas emissions for the Norwegian Coastal Express in a way that emissions reduction targets can be met?

The research question is approached through several sub-questions:

- What are the greenhouse gas emissions of LNG, hydrogen, and ammonia in a well-to-tank perspective?
- What are the greenhouse gas emissions of the alternative fuels in a tank-to-wake perspective?
- What is the overall greenhouse gas emission reduction potential by substituting conventional fuels with low-carbon alternatives?

This chapter has introduced the motivation for reducing greenhouse gas emissions in the shipping sector and the state-of-the-art on climate forces in the shipping sector, alternative shipping fuel substitutes, and well-to-wake emission modeling. The following chapters present the methodology and case study, as well as the results and discussion. The methodology chapter describes the methodology applied for the estimation of well-to-tank emissions and tank-to-wake emissions in detail. Further on, a description of the case study is given in Chapter 3. The chapter outlines the scope of the study, including selected ship segment and alternative fuels. The results are presented in Chapter 4 and further discussed with implications and limitations in Chapter 5.

2 Methodology

In this section, the methodology used for the estimation of well-to-wake emissions is presented. To better understand the origin of the emissions, well-to-tank and tank-to-wake emissions are estimated separately.

2.1 Calculation of well-to-tank emissions

This thesis consists of two different approaches for analyzing well-to-tank emissions. Firstly, a literature review is conducted to provide an overview of the existing research on well-to-tank emissions of the assessed alternative shipping fuels. Additionally, a parametric analysis is performed to obtain well-to-tank emission results that are relevant to Norwegian coastal shipping.

2.1.1 Literature review

The first part of this thesis starts with a literature review to map current well-to-tank emission studies and their research conclusions. In order to achieve a comprehensive picture of well-to-tank emissions, results that are not initially considered to be directly applicable to Norwegian coastal shipping have also been included. This results in a broad overview of how various factors and production conditions influence well-to-tank emissions.

Relevant papers have mainly been found through NTNU's own library service, Oria, in addition to Web of Science, Google Scholar, and Scopus. All papers included in the literature review are peer-reviewed. Figure 2 shows the different search terms and combinations used to find relevant papers. All terms in the first column are combined with terms in the second column, e.g. "well-to-wake" + "ammonia" or "on-site emissions" + "H2".

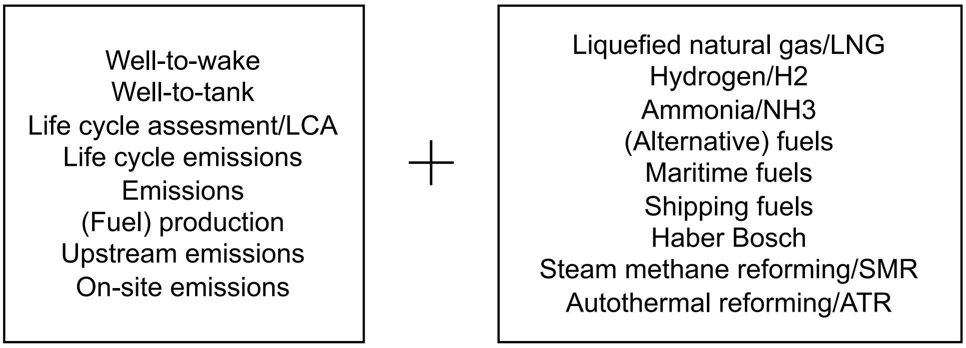


Figure 2: Combination of search terms used for the literature review. Each term in the left box is combined with all terms in the right box.

Many of the relevant studies have other functional units than the one used in this thesis. As far as possible, the results have been harmonized in order to achieve the same functional unit; gCO_2eq/MJ fuel. Papers with no adequate information needed for conversion to this functional unit are excluded from the literature review. For the papers that have not converted emissions species to GWP100, the emission species has been converted to CO_2eq using GWP100 conversion factors from the fifth Intergovernal Panel on Climate Change (IPCC) assessment report [20]. If not clarifying otherwise, it is assumed that CO_2eq emissions are GWP100 values.

Some of the papers categorize emissions in fuel pathway sections, while other papers do not. There are variations of which and how many fuel pathway sections that are included, and also the terms used for each section vary. Table 1 shows how the different pathway sections in the literature have been harmonized into five categories to enable comparison. The five harmonized categories are upstream emissions, on-site emissions, storage emissions, and distribution and transport emissions.

Table 1: Categorization of fuel pathway sections. The table shows how fuel pathway section terms used in the included studies are harmonized into five fuel pathway sections; upstream emissions, on-site emissions, electricity emissions, storage emissions, and distribution and transport emissions. The table also shows pathway sections that are excluded in the literature review.

	Categorized fuel pathway sections	**Included fuel pathway sections**
LNG		
	Upstream emissions	NG production
		NG production and pipeline transport
		NG distribution
		NG total emissions
	On-site emissions	NG liquefaction
		NG purification
		Purification and liquefaction
	Storage emissions	LNG terminal storage
		LNG terminal
	Distribution and transport emissions	LNG transport
		LNG distribution
		LNG distribution
Hydrogen		
	Upstream emissions	NG production
		NG production and transport
		Upstream NG emissions
	On-site emissions	On-site emissions
		Electrolysis
		Operation
		Operation and maintenance
	Electricity emissions	Electricity generation
		Electricity emissions
	Storage emissions	Hydrogen storage
	Excluded in this thesis	Construction of plant
		Manufacturing and operation of wind turbines
		PV manufacturing
		Emissions related to variations in solar energy
Ammonia		
	Upstream emissions	H2 production
	On-site emissions	Haber Bosch (HB) emissions
		Air Separation Unit (ASU) emissions

Studies with other fuel production methods or technologies that are not aligned with the scope of this thesis are excluded form the literature review. The scope is further described in chapter 3.1.1. For grey hydrogen production, Autothermal Reforming (ATR) and Steam Methane Reforming (SMR) are the only included reforming technologies. Water electrolysis, both alkaline and Proton Exchange Membrane (PEM), is the only green hydrogen production method considered. However, many papers do not include what kind of electrolysis that is assessed in the study. All kind of electrolysis is therefore considered as water electrolysis, even though emissions will vary across technologies. For ammonia, this study only includes ammonia synthesis with the Haber-Bosch process.

2.1.2 Parametric analysis

The literature review results in a wide range of well-to-tank emissions. To better understand how certain parameters influence emissions, a harmonization parametric analysis is conducted. With parameters relevant to fuel production in Norwegian, the analysis also enables the estimation of well-to-tank emissions for Norwegian coastal shipping. The analysis is scripted in Python and the code is available in the appendix A.

Table 2 includes all parameters used in the analysis. The table includes the energy content of natural gas, hydrogen, and ammonia, and electricity demand and feedstocks in the methane reforming processes, electrolysis, and ammonia synthesis process. Energy content, electricity demand, methane leakage, and feedstocks are collected from relevant literature and the molar masses are collected from the periodic table. Hydrogen storage emissions and natural gas upstream emissions are based on the performed literature review (lit.) in this thesis. Carbon capture and storage rate (CCS) and electricity emissions are further explored in chapter 3.3. All equations used in the analysis are provided in this chapter.

Table 2: List of parameters and associated values used in the parametric analysis.

Parameter	Abbreviation	Value	Unit	Source
Energy content				
Natural gas	EC_NG	50	MJ/kg	[36]
Hydrogen	EC_H2	120	MJ/kg	[25]
Ammonia	EC_NH3	18.8	MJ/kg	[25]
Electricity demand				
Methane reforming	El_reforming	2.3	kWh/kg H2	[37]
Electrolysis	El_electrolysis	55	kWh/kg H2	[38]
Haber-Bosch process	El_HB	0.75	kWh/kg NH3	[39]
Feedstock				
Natural gas feedstock, reforming	NG_feedstock	2.5	kg NG/ kg H2	[37]
Hydrogen feedstock, Haber-Bosch	H2_feedstock	178	kg H2/ ton NH3	[40]
Nitrogen feedstock, Haber-Bosch	N2_feedstock	822	kg N2/ ton NH3	[40]
Molar masses				
Carbon	M_C	12	g/mol	[41]
Carbon dioxide (CO_2)	M_{CO_2}	44	g/mol	[41]
Methane (CH_4)	M_{CH_4}	16	g/mol	[41]
Variables				
Carbon capture and storage rate	CCS	60 - 98	%	Lit.
Methane leakage	CH4_leakage	2	%	[42]
Hydrogen storage emissions	Storage	1.42	gCO2$_2$eq/MJ	[43]
Natural gas upstream emissions	NG_upstream	9.2	gCO2$_2$eq/MJ	Lit.
Electricity emissions	El_emissions	12-300	gCO2eq/kWh	[44, 45]

Grey and blue hydrogen

Emissions related to grey and green hydrogen production consist of storage emissions, upstream emissions, and production emissions (on-site emissions), including electricity emissions. For blue hydrogen, a certain amount of the onsite-emissions are "captured" and not emitted. The equations used for calculation of well-to-wake emissions for grey and blue hydrogen are given in equation 1 and 2. CCS is the carbon capture rate, while EC_H2 is the energy content of hydrogen.

$$\text{WTT emissions grey H2} = \frac{\text{Upstream} + \text{On-site} + \text{Electricity}}{\text{EC\_H2}} + \text{Storage} \tag{1}$$

$$\text{WTT emissions blue H2 } = \frac{\text{Upstream} + \text{On-site} \cdot (1 - \text{CCS}) + \text{Electricity}}{\text{EC\_H2}} + \text{Storage} \tag{2}$$

The upstream emissions, on-site emissions, and electricity emissions used in the previous equations are calculated in equation 3, 4 and 5. NG_feedstock is the feedstock of natural gas in the reforming process, EC_NG is the energy content of natural gas, and CH4_leakage is the leakage rate of methane in the transport pipelines. NG_upstream is the upstream emissions of natural gas, and the value is collected from the literature review. M_C, M_{CH_4} and M_{CO_2} are the molar mass of carbon, methane and CO_2 respectively. El_reforming is the electricity demand in the reforming process and El_emissions are the emissions related to electricity production.

$$\text{Upstream emissions} = \text{NG\_feedstock} \cdot \text{NG\_upstream} \cdot \text{EC\_NG} \cdot (1 + \text{CH4\_leakage}) \tag{3}$$

$$\text{On-site emissions} = \text{NG\_feedstock} \cdot \frac{M_C}{M_{CH4}} \cdot \frac{M_{CO2}}{M_C} \tag{4}$$

$$\text{Electricity emissions} = \text{El\_reforming} \cdot \text{El\_emissions} \tag{5}$$

Green hydrogen

The only upstream emissions related to green hydrogen are the emissions from the electricity used for electrolysis. Together with storage emissions, electrolysis emissions form the well-to-tank emissions for green hydrogen, as shown in equation 7. Equation 6 shows how the electrolysis emissions are calculated. El_electrolysis is the electricity demand for the electrolysis process.

$$\text{Electrolysis emissions} = \text{El\_electrolysis} \cdot \text{El\_emissions} \tag{6}$$

$$\text{WTT green H2} = \frac{\text{Electrolysis}}{\text{EC\_H2}} + \text{Storage} \tag{7}$$

Ammonia

Well-to-tank emissions of ammonia consist of hydrogen production emissions (upstream emissions), ammonia synthesis emissions (on-site emissions), and storage emissions, as visualized in equation 8. The equation is equal for all three types of ammonia (grey, blue, and green). The only difference between the three different types of ammonia is the production method of the hydrogen feedstock. Storage emissions for ammonia are calculated as a percentage (x) of hydrogen storage emissions, as no explicit data on ammonia storage emissions are available in the reviewed literature. EC_NH3 is the energy content of ammonia.

$$\text{WTT emissions NH3} = \frac{\text{Upstream} + \text{NH3 synthesis}}{\text{EC\_NH3}} + x \cdot \text{Storage} \tag{8}$$

The upstream emissions and NH3 synthesis emissions are estimated with equation 9 and 10. The upstream emissions are equal to upstream, on-site, and electricity emissions of the hydrogen feedstock production multiplied by how much hydrogen is needed to produce one amount of ammonia (H2_feedstock). El_HB is the electricity demand in the Haber-Bosch process.

$$\text{Upstream emissions} = \text{Hydrogen upstream, on-site and electricity emissions} \cdot \text{H2\_feedstock} \tag{9}$$

$$\text{NH3 synthesis emissions} = \text{El\_HB} \cdot \text{El\_emissions} \tag{10}$$

2.2 Calculation of tank-to-wake emissions with the MariTEAM model

The tank-to-wake emissions of the ship segment presented in chapter 3.1.2 are calculated with the MariTEAM model. The model is a full bottom-up approach, calculating tank-to-wake emissions based on fuel consumption. The fuel consumption is calculated by using the ship's operational profile, as well as ship location and weather conditions. The model is developed by the Industrial Ecology Programme at NTNU and performs a complete well-to-wake emissions assessment, including Life Cycle Assessment (LCA) of fuel production and ship emissions. In this thesis, the MariTEAM model is only utilized for tank-to-wake emissions. [4]

Ship location data and weather data are collected from AIS, which is an identification system for ships. The AIS equipment onboard sends out information about the ship, typically position, speed, and course, in addition to vessel information. AIS is mandatory for all vessels with gross tonnage larger than 300 tons. Dynamic data is sent every three minutes if the speed is lower than three knots and every ten seconds if the speed is between three and 14 knots. If the speed is higher, the data is sent every two seconds. Other data (name, IMO-number, vessel dimensions) is sent every six minutes. Information about cargo, destination, etc., can be sent voluntarily. [1, 46]

The MariTEAM model combines Specific Fuel Consumption (SFOC) and load conditions at the engine (P_S) to calculate fuel consumption. By multiplying fuel consumption with the Content of carbon or sulphur present in fuel (FC), CO_2 emissions can be estimated. Δt is the time between each data point, which correlates to the AIS data. The calculation of direct combustion emissions is shown in equation 11, where i is the pollutant being assessed, j is the engine, and k is the route. [4]

$$E_{i,j,k} = \Sigma_j Ps_{j,k} \cdot SFOC_{i,j} \cdot FC_{j,k} \cdot \Delta t_k \tag{11}$$

For calculation of the resisting greenhouse gases (CH_4 and N_2O), equation 12 is used. These pollutants depend on combustion conditions, rather than the fuel's chemical composition. For these emission estimations, shaft power (P_S) is multiplied with Emission Factors (EF) and Engine load as a percentage of maximum continuous rating (LF). [4]

$$E_{i,j,k} = \Sigma_j Ps_{j,k} \cdot EF_{i,j} \cdot LF_{j,k} \cdot \Delta t_k \tag{12}$$

For ship technical reasons, LNG, hydrogen, and ammonia are not suited as fuels when the engine load is lower than 10 %. In these cases, the MariTEAM model replaces the alternative fuel with MGO. The cases with engine load lower than 10 % are extraordinary, but will cause higher tank-to-wake emissions occasionally. [4]

The output of the MariTEAM model is the ship emissions through a given year, distributed over thousands of data points. The time interval between each data point ranges from seconds to minutes. The data collected for this thesis are dated between 01.01.2018 and 31.12.2018. In order to determine emissions per Megajoule (MJ) fuel, the latter must be calculated as the model do not. MJ fuel per data point is calculated with main engine power multiplied by delta time, as shown in equation 13.

$$\text{MJ fuel} = \frac{\text{Main engine power [W]} \cdot \text{delta time [s]}}{10^{-6}\frac{\text{Ws}}{\text{MJ}}} \tag{13}$$

With these modifications, the MariTEAM model now calculates emissions per MJ fuel for each data point. To get one representative value for tank-to-wake emissions per ship, the median value across all data points is calculated. This eliminates outliers in the results. All calculations in this section are retrieved from the support material of the published MariTEAM study [4].
The tank-to-wake emissions are scripted in Python and available in appendix B.

3 Case study

The objective of this thesis is to estimate well-to-wake emissions of alternative fuel substitutes for the Norwegian Coastal Express. In this section, the selection of alternative fuels and the assessed fuel pathways are presented, as well as the ship segment. First, the scope and functional unit of this case study is provided. The section also includes an overview of the papers included in the literature review and assumptions for fuel consumption in Norway.

3.1 Scope and functional unit

The case study includes separate well-to-tank and tank-to-wake assessments of greenhouse gas emissions for the Norwegian Coastal Express. Ideally, the emissions would be suitable with a distance-related functional unit. Because of the fixed route of the studied ship segment, it would be interesting to look at the emission either one way (northbound or southbound) or for a round trip. However, the preliminary project work revealed challenges with distance estimations along the Norwegian coastline when using the MariTEAM model. All emissions in this thesis are therefore calculated per MJ fuel. In this way, the results can easier be adapted to other ship segments as well.

All greenhouse emissions are estimated with GWP100 as emission metric. This metric is the most frequent metric used in relevant studies and makes it possible to calculate well-to-wake emissions by adding together well-to-tank and tank-to-wake emissions. For tank-to-wake emissions, GWP20 is used as an emission metric in addition to GWP100, in order to visualize the differences between these metrics. The conversion factors for these two emission metrics are provided in appendix C and retrieved from the Supplementary Material in IPCC 5th Assessment Report [47].

3.1.1 Selected fuels and fuel pathways

The alternative shipping fuels assessed in this thesis are LNG, hydrogen, and ammonia. For hydrogen and ammonia, production from natural gas with (blue) and without (grey) CCS in the reforming process are included, as well as production with electrolysis (green). A well-to-wake flow chart of the included fuels is visualized in figure 3.

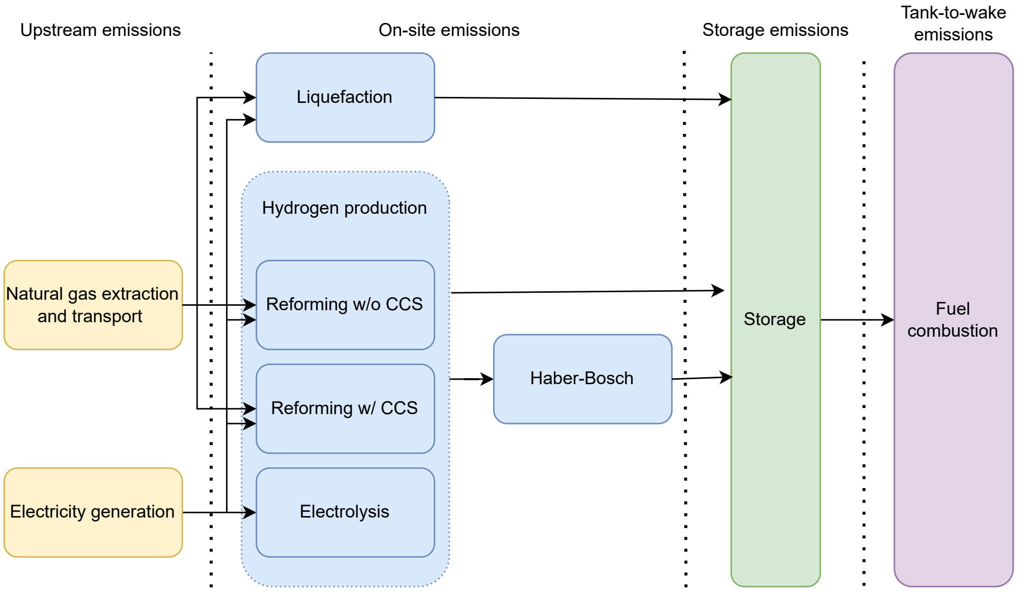


Figure 3: Flow chart of alternative fuel modelling well-to-wake.

Natural gas can be used for the production of both LNG, hydrogen, and ammonia. The only considered pathway of LNG production is liquefaction of natural gas. The fuel pathway of LNG is illustrated in figure 4 For hydrogen production, both SMR and ATR is included as reforming processes. For the electrolysis, renewable energy sources such as wind, solar, and hydropower are included. Some studies report on electrolysis based on grid electricity. This is also included in this study. For ammonia production, the only included production method is the Haber-Bosch process. In addition to LNG, hydrogen and ammonia, the conventional fuels HFO and MGO are included in the tank-to-wake and well-to-wake analysis as business-as-usual scenarios.

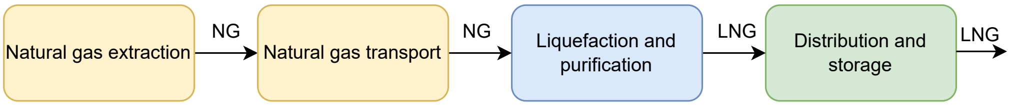


Figure 4: Flow chart of LNG fuel pathway well-to-tank.

As stated in chapter 1, grey and blue hydrogen is produced with natural gas as feedstock. ATR and SMR are the two most mature reforming technologies, with SMR being the most common reforming method used today. The SMR process starts with methane (CH_4) being mixed with steam (H_2O) at high temperatures. This causes carbon oxide (CO) which is then reacting with steam in a water shift reaction. The final products are hydrogen and CO_2. The chemical reactions are described in equation 14 and 15. [6]

$$CH_4(g) + H_2O(G) \leftrightarrow CO(g) + H_2(g) \tag{14}$$

$$CO(g) + H_2O(g) \leftrightarrow CO_2(g) + H_2(g) \tag{15}$$

The key difference between ATR and SMR is the use of high-purity oxygen. In ATR, O_2 is added as a reactant. This causes natural gas to be partially combusted inside the reforming tubes, in order to meet the reforming energy demand. The syngas and flue gas are, as a result, not diluted with nitrogen, which makes the implementation of carbon capture easier.[48]

Hydrogen can also be produced with electrolysis. There are several electrolysis technologies available, but alkaline and PEM electrolysis are the most mature ones. Equal for both technologies is that electricity is used for the separation of water into hydrogen and oxygen, as shown in equation 16. The technologies differentiate in how water is split. [49]

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \tag{16}$$

All assessed hydrogen production pathways are visualized in figure 5.

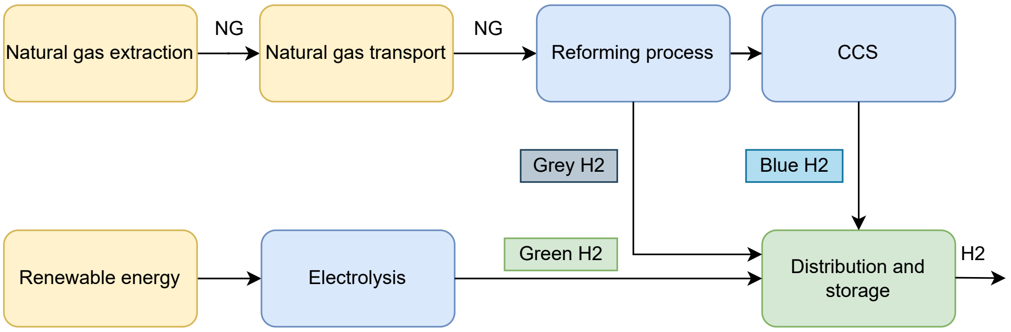


Figure 5: Flow chart of the hydrogen fuel pathway well-to-tank. Natural gas is used to produce grey and blue hydrogen, while green hydrogen is produced via electrolysis.

For ammonia, Haber-Bosch is the only synthesis method assessed in this thesis. In the synthesis process, ammonia is produced by mixing hydrogen and nitrogen, as shown in equation 17 [50].

$$N_2 + 3H_2 \rightarrow 2NH_3 \tag{17}$$

The upstream pathway of ammonia is visualized in figure 6.

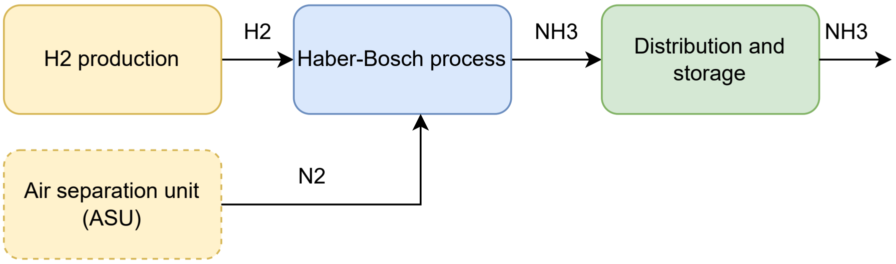


Figure 6: Flow chart of ammonia fuel pathway well-to-tank. Nitrogen is extracted from the air in an Air Separation Unit (ASU) and mixed with hydrogen in the Haber Bosch process.

3.1.2 Ship segment

The aim of this thesis is to investigate how alternative fuels can decarbonize Norwegian coastal shipping. The Norwegian Coastal Express (Kystruten) is chosen as the ship segment, because of its importance for transport and communication for coastal communities in Norway. The coastal express is a traditional shipping institution in Norway and has been in service for 130 years. The vessels are sailing between Bergen and Kirkenes, calling at 34 ports in total. [51] The location of the ports is visualized in figure 7.

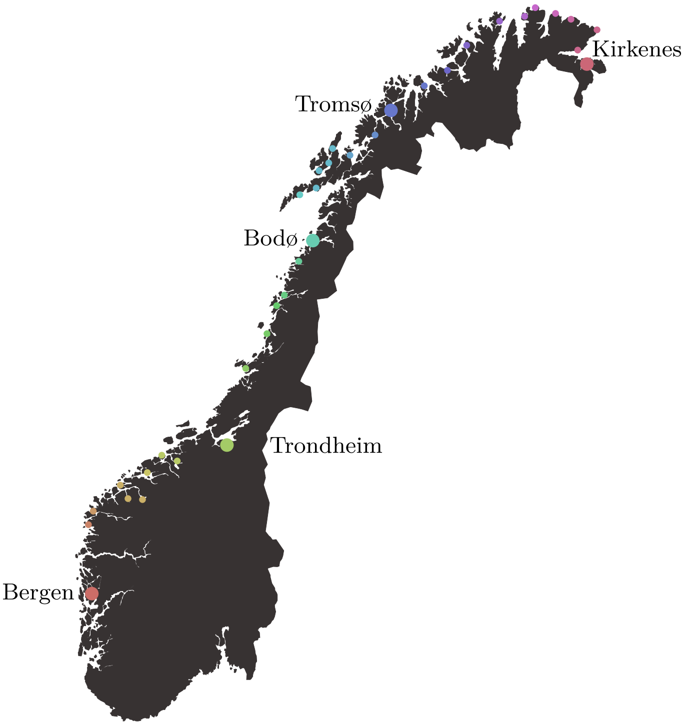


Figure 7: Location of ports visited by the Coastal Express. The ships are sailing between Bergen and Kirkenes, calling at 34 ports in total.

The ships included in this study are presented in table 3. Today the coastal express is operated by twelve ships in total, four of which are operated by the new shipping company *Havila Kystruten* and eight by the traditional company *Hurtigruten* [52]. Since the tank-to-wake emission data is based on shipping activities in 2018, the included ships in this study are the eight ships that operated the route in 2018 and are still operating it today. These eight ships are MS Kong Harald, MS Nordkapp, MS Nordlys, MS Nordnorge, MS Polarlys, MS Richard With, MS Trollfjord, and MS Vesterålen. Table 3 includes Maritime Mobile Service Identity (MMSI), gross tonnage, Deadweight Tonnage (dwt), passenger capacity, year of construction, and year of latest refurbishment for all the ships. MMSI and deadweight tonnage information are gathered from Marine Traffic[2] [53], while remaining information are gathered from Hurtigruten [54].

Table 3: The vessels included in the ship segment and associated vessel information.

Ship	**MMSI**	**Gross tonnage/ dwt**	**Passenger capacity**	**Year of construction/ latest refurbishment**
MS Kong Harald	257200000	11204/902	590	1993/2023
MS Nordkapp	259330000	11386/1104	590	1996/2016
MS Nordlys	259139000	11204/805	590	1994/2019
MS Nordnorge	259371000	11384/1171	590	1997/2016
MS Polarlys	259322000	11341/1150	619	1996/2016
MS Richard With	258500000	11205/850	590	1993/2018
MS Trollfjord	258465000	16140/1186	500	2002/2023
MS Vesterålen	258478000	6261/900	490	1983/2022

The majority of the ships are nearly equal in size and passenger capacity. The smallest ship, MS Vesterålen, has the lowest passenger capacity and was the first one to be built. MS Trollfjord is the newest ship and also the largest one (based on gross tonnage and dwt). Yet it has the second lowest passenger capacity and can only transport 10 more passengers than MS Vesterålen. The rest of the ships were built between 1993 and 1997, and have a passenger capacity of 590-619. It varies what a refurbishment of the ships includes. Often, the interior gets an upgrade, but sometimes the engine is upgraded as well. MS Kong Harald had a significant upgrade in 2023, with new and less emission-intensive hybrid engines with batteries as a supplement. This is to this day the only hybrid ship of the ones assessed in this thesis. [54]

3.2 Included papers in the literature review

Table 4 provides an overview of all papers included in the literature review. 22 papers are included in total, whereof nine of them are LNG emissions studies, eight are studies on hydrogen emissions, and five are studies on ammonia emissions. None of the papers assesses more than one fuel. Only one paper includes both grey, green, and blue hydrogen. Four papers combine grey and blue hydrogen emissions, while three papers combine grey and green hydrogen. For papers assessing ammonia production, three papers combine green and grey ammonia, while one paper combines blue and green ammonia. Only one paper combines all three ammonia production methods.

---

[2] Database of marine traffic. Available at https://www.marinetraffic.com/

Table 4: Overview over included papers in the literature review and which fuels the paper assess.

Paper	**LNG**	**Hydrogen**			**Ammonia**		
		Grey	Blue	Green	Grey	Blue	Green
Jaramillo et al., 2007 [55]	X						
Manouchehrinia et al., 2020 [28]	X						
Okamura et al., 2007 [56]	X						
Arteconi et al., 2010 [26]	X						
Verbeek et al., 2011 [57]	X						
Hwang et al., 2019 [58]	X						
Jang et al., 2021 [59]	X						
Tagliaferri et al., 2017 [60]	X						
Brynof et al., 2014 [61]	X						
Oni et al., 2022 [37]		X	X				
Salkuyeh et al., 2017 [48]		X	X				
Antonini et al., 2020 [30]		X	X				
Hydrogen Council, 2021 [62]		X	X	X			
Chugh et al., 2022 [63]		X		X			
Kanz et al., 2021 [49]				X			
Fernandez-Dacosta et al., 2019 [6]		X		X			
Cetinkaya et al., 2012 [43]		X		X			
Boero et al., 2021 [64]					X	X	X
Chisalita et al., 2020 [65]						X	X
Ghavam et al., 2021 [66]					X		X
Al-Aboosi et al., 2021 [32]					X		X
Smith et al., 2020 [33]					X		X

Some papers included specific emissions related the one or several sections of the fuel pathway. Table 5 shows how many values are extracted from the literature, separated by fuel pathway sections harmonized in chapter 2.1.1. Emissions related to distribution and transport are only provided for LNG, while storage emissions are only offered by LNG and green hydrogen.

Table 5: Number of values extracted from the literature in each specific fuel pathway section.

	LNG	**Hydrogen**			**Ammonia**		
		Grey	Blue	Green	Grey	Blue	Green
Total well-to-tank emissions	11	20	20	30	7	3	14
Upstream emissions	7	3	3	-	3	-	5
On-site emissions	17	3	3	1	2	-	1
Electricity emissions	-	3	3	-	-	-	-
Storage emissions	4	-	-	1	-	-	-
Distribution and transport emissions	7	-	-	-	-	-	-

3.3 Fuel consumption in Norway

The upstream emissions of fuel consumed in coastal shipping in Norway are conditioned by production location and process technology. This includes electricity emissions and CCS rate. To better understand how electricity emissions and CCS rate influence upstream emissions, a parametric analysis is performed.

Emissions related to electricity depend on the energy used for electricity generation. Electricity generated by renewable energy will have a lower carbon footprint than electricity generated by fossil fuels [67]. Electricity generated by hydropower has a carbon footprint of 24 gCO_2eq/kWh, while electricity with origin in wind power and solar power equals 12 and 41 - 48 gCO_2eq/kWh respectively [44]. The electricity grid mix in Norway is dominated by renewable energy, mainly hydropower (81 %) and wind power (12 %). This results in a carbon footprint of 19 gCO_2eq/kWh. [68] The European grid mix on the other hand is based on fossil fuels and has a carbon footprint of 200-300 gCO_2eq/kWh [45, 69].

The CCS rate has increased with technology improvements and the technology continues to be improved. Depending on the CCS technology and type of methane reforming process, the CCS rate will typically vary between 85 % and 95 %. [30] It is expected that the rate can be as high as 98 % within a few years [62].

In the parametric analysis, the well-to-tank emissions are calculated by taking into account the changes in electricity emissions and CCS rate. By maintaining a constant CCS rate of 90%, the impact of electricity emissions are evaluated by varying it from 12 to 300 gCO_2eq/kWh. Similarly, the electricity emission is fixed at 19 gCO_2eq/kWh and the CCS rate is varied between 60 and 98% to measure the influence of the CCS rate.

4 Results

In this section, the results of the well-to-wake analysis are presented. First, the well-to-tank emissions extracted from the literature review and estimated in the parametric analysis are presented. Following are the details of the tank-to-wake emissions calculated with the MariTEAM model introduced. Lastly, the well-to-tank and tank-to-wake emissions are combined in a complete well-to-wake analysis.

4.1 Well-to-tank emissions

The literature review reveals significant variations of well-to-tank emissions for the assessed fuels. Figure 8 provides a box plot of the well-to-tank emissions extracted from the examined literature. Only total well-to-tank emissions are considered in the visualization.

The box plots illustrate the distributions of the results. The green line marks the median of all values extracted from the literature. The upper and lower black line represents the maximum and minimum value, respectively. 50% of the extracted values are within the blue outlined box, 25% of them below the median value line, and 75% above the median value line. The black outlined dots are outliers, i.e., values that are distinct from the other values. The red dots indicate the well-to-tank emissions calculated in the parametric analysis. This is further investigated later in this chapter.

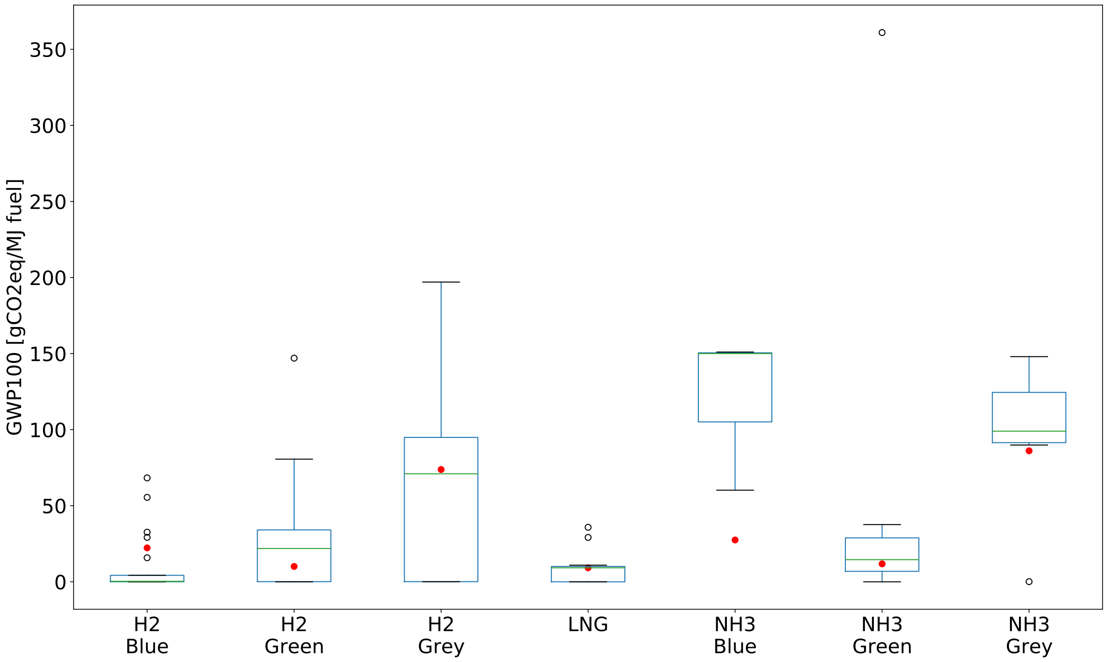


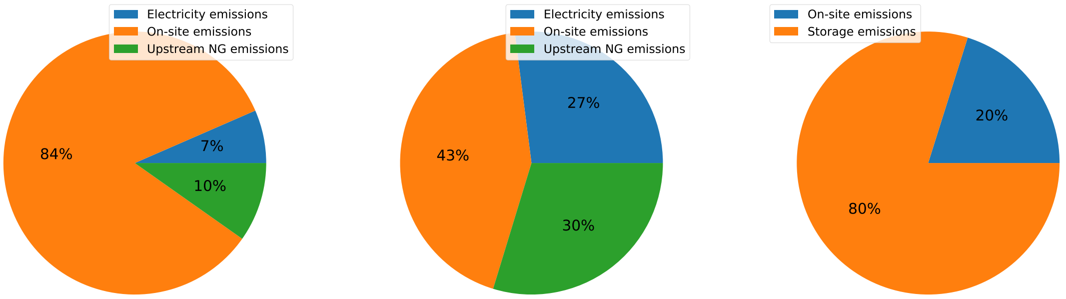
Figure 8: The box plots illustrate the distribution of reported well-to-tank emissions that are retrieved in the literature review. The figure shows the median value (green line), minimum and maximum values (black lines), and outliers (black outlined dots) of well-to-tank emissions for each alternative fuel. 50 % of the extracted values are inside the boxes. The red dots indicate the well-to-tank emissions calculated in the parameter analysis.

Figure 8 shows that the gap between the minimum and maximum value is especially high for green and grey hydrogen and green, blue, and grey ammonia. The distribution of extracted values for blue hydrogen and LNG is narrow but excludes outliers close by. For blue hydrogen, there are five outliers and for LNG there are two. These account for 25 % and 18 % of the total amount of extracted values respectively. Green hydrogen, green ammonia, and grey ammonia all have one outlier quite distinct from the maximum or minimum value. The median values represented with the green line in the box plots are stated in table 6.

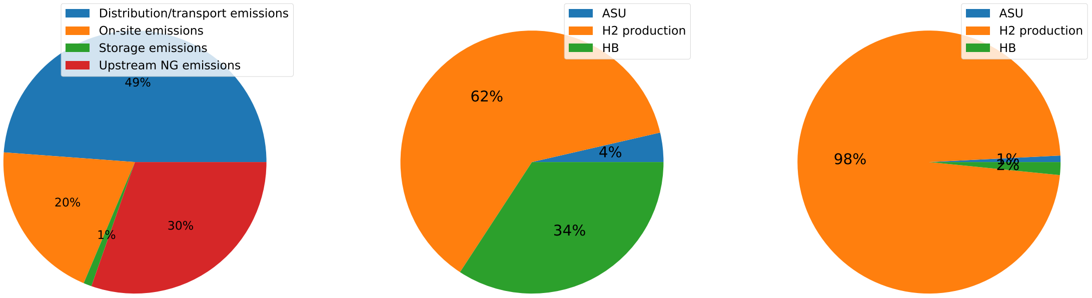
Table 6: Median value of the alternative fuels' well-to-tank emissions retrieved from the literature review.

Alternative fuel	**Well-to-tank emissions** [gCO$_2$eq/MJ fuel]
LNG	9.21
Grey H2	71.0
Blue H2	0.32
Green H2	21.9
Grey NH3	99.0
Blue NH3	150
Green NH3	14.6

When assigning the well-to-wake emissions to specific pathway sections, the results reveal variations in the importance of each section among the alternative fuels. In figure 9, the emissions related to each individual section of the fuel pathways are illustrated.



(a) Grey H2 (b) Blue H2 (c) Green H2



(d) LNG (e) Grey NH3 (f) Green NH3

Figure 9: Emissions related to specific fuel pathway sections well-to-tank. On-site emissions make up the biggest share of grey and blue hydrogen emissions well-to-tank, while upstream emissions are the most emission-intensive process for ammonia. Storage emissions make up 80 % of green hydrogen emissions, while transport and distribution emissions make up almost half of the LNG emissions.

For grey and blue hydrogen, the majority of emissions come from on-site activities. Upstream emissions only make up 10% of the total emissions for grey hydrogen, while it's 30% for blue hydrogen. As for green hydrogen, most of the well-to-tank emissions are attributed to hydrogen storage, while upstream emissions from electrolysis account for 20% of the total emissions. Regarding LNG, almost half of its total emissions originate in the distribution and transport, followed by 30% of upstream emissions and 20% from on-site activities. The storage of LNG only contributes 1% to the total well-to-wake emissions. For grey and green ammonia, hydrogen production is equivalent to upstream emissions, while on-site emissions come from Air Separation Unit (ASU) emissions and Haber Bosch (HB) emissions. For grey ammonia, hydrogen production contributes to 62% of the well-to-tank emissions, followed by 34% from Haber Bosch emissions and only 4% from Air Separation Unit (ASU) emissions. For green ammonia on the other hand, Haber Bosch and ASU emissions can make up as little as 2% and 1%, respectively, while the remaining emissions are caused by the production of hydrogen.

The well-to-tank emissions are influenced by several parameters. Figure 10 and 11 present the influence of CCS rate and electricity emissions on the well-to-tank emissions for the alternative fuels. The assessed CCS rates are 60 %, 90 %, and 98 %, while the electricity emissions vary between 12 and 300 gCO_2eq/kWh.

In figure 10, the dark blue bar represents the emissions with a 98 % CC rate. With this rate, the upstream emissions of blue hydrogen are 76% lower than the upstream emission of grey hydrogen. The emissions increase with lower CCS rates. If only 60 % of the emissions produced on-site are captured, the GHG emissions of blue hydrogen will be 47% lower than of grey hydrogen. Note that CCS will only apply to blue hydrogen and blue ammonia and therefore not influence LNG or grey and green hydrogen and ammonia.

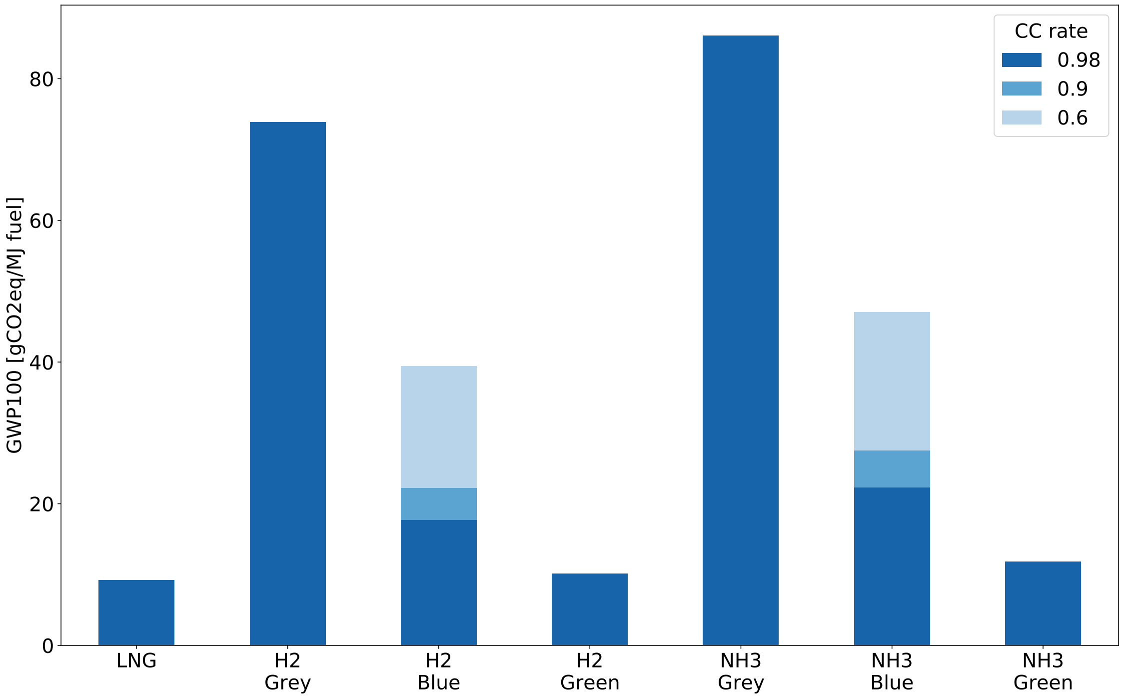


Figure 10: The influence of carbon capture and storage rate (CCS rate) on well-to-tank emissions. A CCS rate of 90 or 98 % will result in significantly lower well-to-tank emissions for blue hydrogen, than a CCS rate of 60 %.

The influence of electricity emissions is illustrated in figure 11. In instances where electricity emissions are equivalent to 300 g CO_2eq/kWh, green hydrogen generates nearly 40% more emissions than grey hydrogen in a well-to-tank perspective. Reducing the electricity emissions to 200 g CO_2eq/kWh affects the well-to-tank emissions of green hydrogen and ammonia significantly. Considering green hydrogen together with grey ammonia, they will still be the most emission-intensive alternative fuels. With electricity emissions equal to 12 and 19 gCO_2eq/kWh however, the well-to-tank emissions of the assessed fuels seem entirely different. If the electricity is generated by renewable energy, green hydrogen, and green ammonia will, together with LNG offer the lowest well-to-tank emissions of all assessed alternative fuels. It is important to note that electricity emissions significantly affect well-to-tank emissions for ammonia. This is due to the energy-intensive Haber Bosch process.

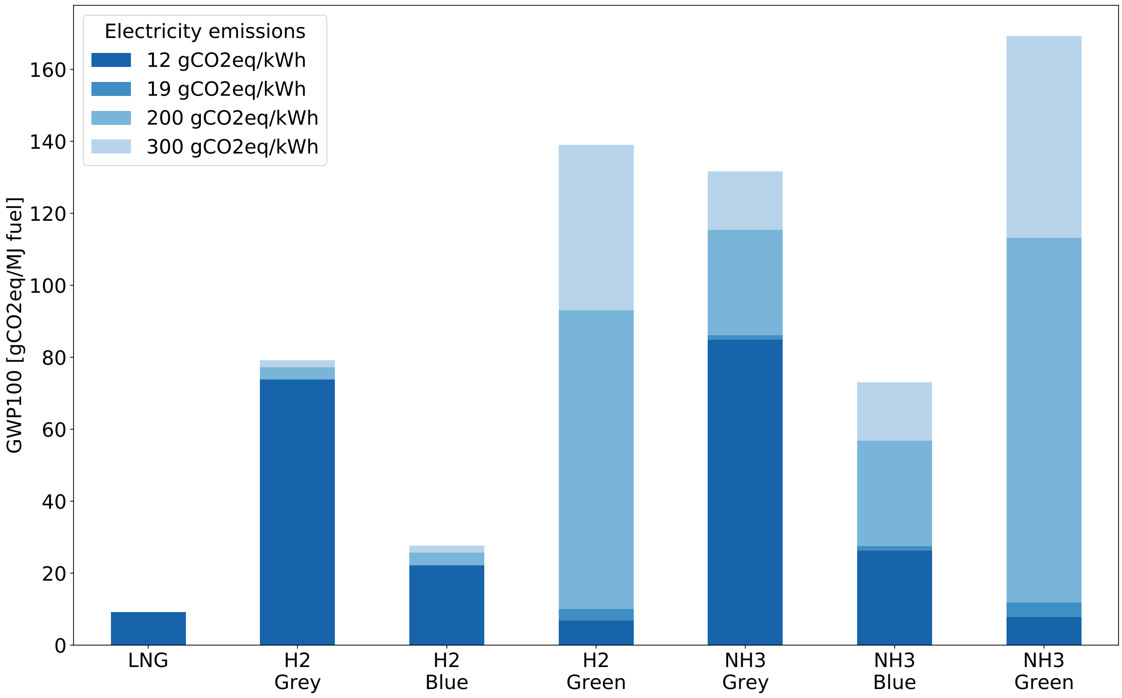


Figure 11: The influence of electricity emissions on well-to-tank emissions. Electricity emissions are of significant importance, especially for green hydrogen and green ammonia. Grey and blue ammonia will also be heavily influenced by electricity emissions.

For the estimation of well-to-wake emissions, a representative well-to-tank emission estimate per fuel is needed. A CCS rate of 90 % is considered representative based on the technology available today. Assuming that the fuel is produced in Norway, electricity emissions will be 19 gCO_2eq/kWh. The well-to-tank emissions calculated with these assumptions are stated in table 7. The estimates are also visible as red dots in figure 8. Well-to-tank emissions of the conventional fuels HFO and MGO are also included in the table. These emissions are calculated with the MariTEAM model.

Table 7: Well-to-tank emissions assuming electricity emissions equal to 19 gCO_2eq/kWh and a CCS rate of 90%.

Shipping fuel	**Well-to-tank emissions** [g CO_2eq/MJ fuel]
LNG	9.2
Grey H2	73.8
Blue H2	22.3
Green H2	10.1
Grey NH3	86.1
Blue NH3	27.5
Green NH3	11.8
HFO	9.4
MGO	13.9

4.2 Tank-to-wake emissions

The tank-to-wake emissions of the Norwegian Coastal Express are calculated with the MariTEAM model. Figure 12 shows the greenhouse gas emissions from each of the alternative fuels, as well as the conventional ones, in a tank-to-wake perspective. With the MariTEAM model calculations, GHG emissions are reduced by approximately 25% with LNG and 75 % with ammonia compared to conventional fuels. As expected there are barely any tank-to-wake emissions with hydrogen as fuel. The minimal amount of GHG emission is due to the use of LNG in abnormal engine conditions. The emission estimates are based on all ships in the ship segment. There are some variations in tank-to-wake emissions among the ships, but none of the variations are significant. The variations are caused by the ships' operational profile, with variations in weather conditions for example. The tank-to-wake emissions for each ship are presented in appendix D.

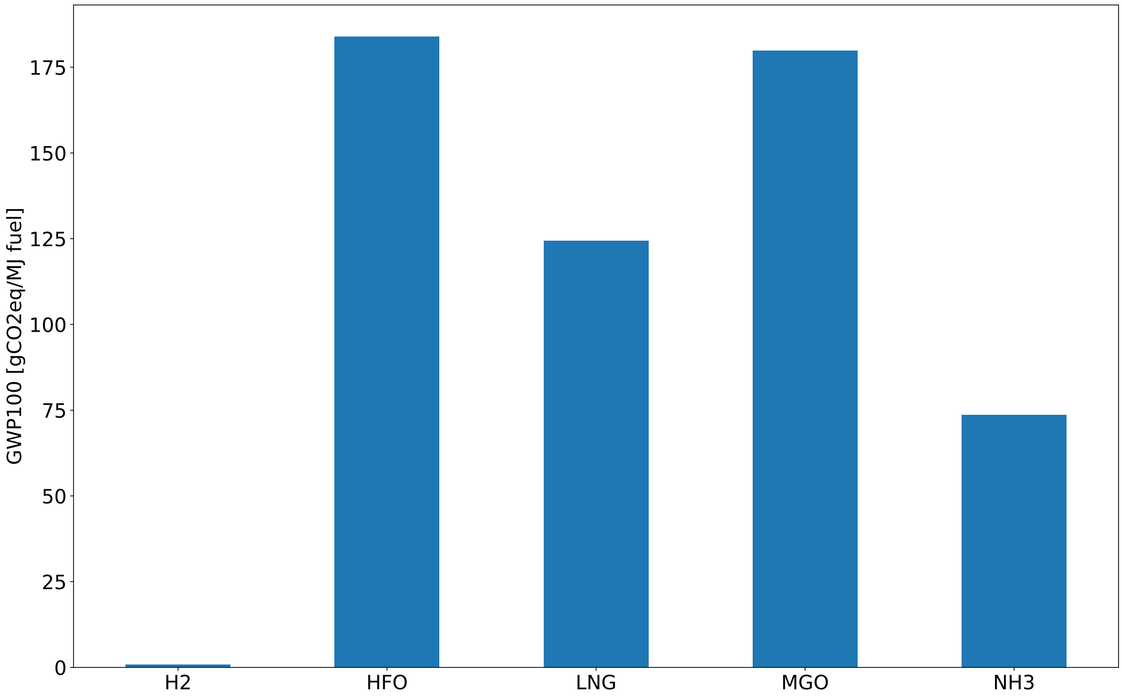


Figure 12: Tank-to-wake emissions calculated with the MariTEAM model. The results show a 25% reduction of GHG emissions for LNG, a 75% reduction for ammonia, and 100 % reduction for hydrogen, compared to conventional fuels (HFO and MGO).

The MariTEAM model's features allow for the calculation of individual greenhouse gas contributions. This enables calculations of multiple emission metrics, including GWP100 and GWP20. Figure 13 and 14 show the share of global warming potential (GWP) of CO_2, CH_4 and N_2O emissions for all fuels in a 100- and 20-year perspective, respectively. In both emission metrics, CO_2 is the most important emission driver for HFO, MGO and LNG. For ammonia, N_2O emissions contribute the most to Global Warming Potential (GWP), while CH_4 emissions are the most important emission driver for hydrogen consumption. Most importantly, these graphs show how CH_4 contributes more to the total emissions in a 20-year perspective than in a 100-year perspective.

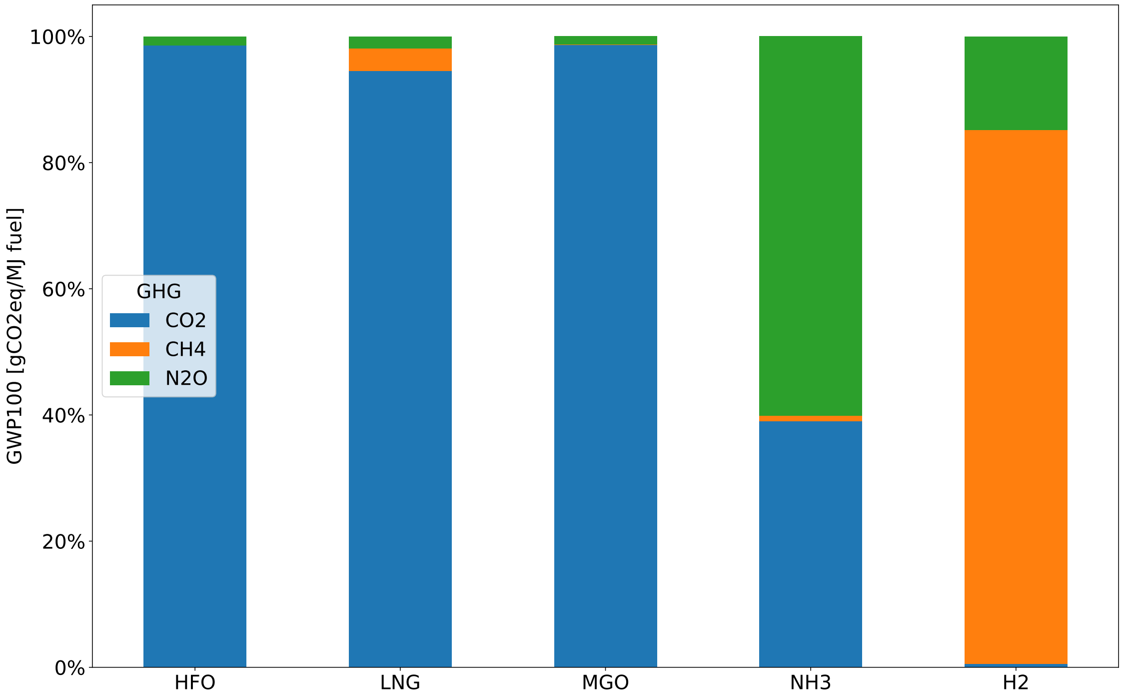


Figure 13: Contribution of CO_2, CH_4, and N_2O emissions to GWP100, tank-to-wake. CO_2 make up the biggest share of GWP100 for HFO, MGO, and LNG. N_2O make up the biggest share for ammonia, while CH_4 emissions are the most important for hydrogen.

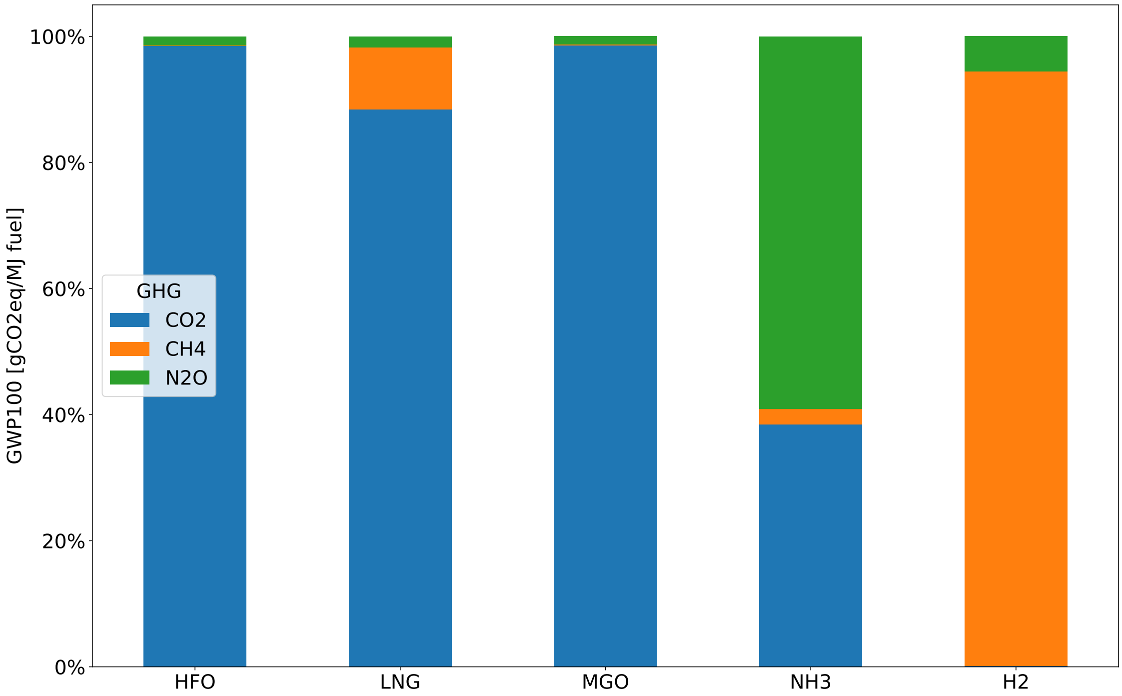


Figure 14: Contribution of CO_2, CH_4, and N_2O to GHG emission to GWP20, tank-to-wake. The results show how CH_4 emissions make up a bigger share of GWP20 than of GWP100.

4.3 Well-to-wake emissions

The overall well-to-wake emissions for the Norwegian coastal express are visualized in figure 15. The well-to-tank emissions obtained from the parametric analysis, assuming all electricity is of Norwegian grid origin and a CCS rate of 90 %. The tank-to-wake emissions are obtained from the MariTEAM model.

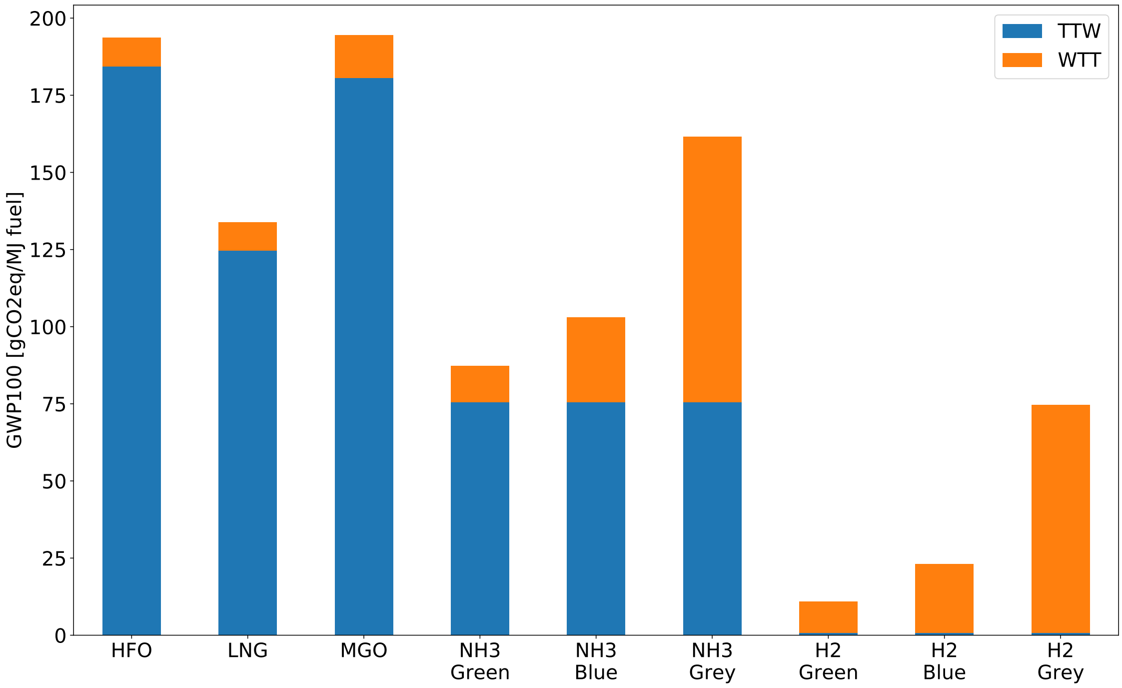


Figure 15: Well-to-wake emissions for the Norwegian Coastal Express using alternative or conventional shipping fuels. The results show emission reduction potential for all assessed alternative fuels. Hydrogen has the lowest GHG emissions, followed by green and blue ammonia.

All alternative fuels offer lower GHG emissions over their life cycle than the conventional ones, given that the fuels are produced with electricity generated by renewable energy and a CCS rate of 90 %. Green and blue hydrogen will offer the greatest reduction of GHG emissions if the electricity used for electrolysis and methane reforming is produced with renewable energy. By the same assumption, green ammonia will have lower GHG emissions than both blue ammonia and grey hydrogen. If the ammonia is produced from grey hydrogen, all the other alternative fuels, including LNG will offer a greater GHG emission reduction.

5 Discussion

There is consensus among scientists that reducing greenhouse gas emissions is essential for mitigating climate change. The shipping sector is one of the sectors where the reduction of greenhouse gas emissions has been insufficient to date, and increasing demand for maritime transportation will require other mitigation tools than reducing the activity. Substituting conventional fuels with low-carbon alternatives is suggested as one potential solution.

Reducing greenhouse gas emissions can be quite challenging due to discrepancies in the quantification of emission data. Different models often result in varying emissions data. Well-to-wake models provide a comprehensive evaluation of the entire life cycle emissions of maritime fuels, from production to combustion. This enables decision-makers to make informed choices about which alternative fuels should replace conventional ones.

In this thesis, a complete well-to-wake analysis of low-carbon fuel alternatives has been developed in order to find out which fuel will cause the lowest greenhouse gas emissions for the Norwegian Coastal Express. The MariTEAM model is combined with a well-to-tank analysis of upstream fuel emissions in Norway.

5.1 Main findings

The literature review reveals a wide range of reported well-to-tank emissions in the literature. The range in reported well-to-tank emissions is especially wide for green and grey hydrogen and all ammonia production methods. The differences can be explained by different baseline assumptions and reference scenarios, including variations in fuel production technology, regional differences, transport distance, or electricity origin. There are also variations in what parts of the fuel pathway are included, or excluded.

The range of reported well-to-tank emissions of LNG is less wide than for other alternative fuels. As a mature technology that is already applied to several ships, the emissions are plausibly quantifiable and more certain than other alternative fuels. There are still some variations, but the well-to-tank emissions are overall relatively low. For hydrogen and ammonia, the range between the maximum and minimum reported well-to-tank emission varies based on the production method. The range is wide for grey and green hydrogen, while for blue hydrogen the range is less wide. Based on figure 9d, the amount of emissions emitted during the production of green hydrogen is heavily influenced by the source of electricity. This explains why the well-to-tank emissions for green hydrogen vary significantly. However, it is more challenging to determine the emissions associated with grey hydrogen since most of the emissions occur on-site and are not as dependent on the electricity source as those of green hydrogen. The reported well-to-tank emissions of blue hydrogen, which are directly linked to grey hydrogen production, do not vary equally significantly. This further undermines the reported emissions associated with grey hydrogen. In contrast to grey hydrogen, blue hydrogen is still an immature technology that is not implemented in large-scale environments at this point. For ammonia, the ranges of well-to-tank emission estimates vary between approximately 80 and 180 gCO_2eq/MJ. Emission estimates for green ammonia vary the least and are also based on the most values included in the review compared to grey and blue ammonia. For blue hydrogen, the results are based on only three emission estimates, whereof two of them are more or less equal. Studies on hydrogen and ammonia are in general more recent, and to a larger degree based on assumptions and technical possibilities than observed values compared to LNG.

In the examination of emissions associated with specific sections of the fuel pathways, there are variations of which section that is most emission-intensive across the assessed fuels. On-site emissions account for 84 % of total emissions for grey hydrogen and 43 % for blue hydrogen. Meanwhile, storage emissions make up 80 % of the emissions for green hydrogen, but only 2 % for LNG. For grey and blue hydrogen and grey and green ammonia, storage emissions are not included in any of the papers in the literature review. Storage emissions will be equal for all hydrogen production methods, as there are no differences in the properties of the hydrogen as a product. Storage emissions of ammonia will most likely be lower than for hydrogen, because of higher liquefaction temperature. Upstream emissions are the most emission-intensive pathway section for both LNG, and grey and green ammonia. For ammonia, upstream emissions are equal to hydrogen production emissions, meaning that the *H2 production* section in grey and green ammonia includes all sections in the pie charts of grey and green hydrogen. None of the studies on blue ammonia includes pathway emissions in its study. There are massive gaps missing to make emissions of the different fuel pathways complete, but the results give an indication of where the emissions originate. The results are therefore included in this thesis, but this is definitely an area of improvement.

To deal with the variations of well-to-tank emissions in the literature review, a more specific approach was needed in order to sort out the fuel production emissions suitable to fuel consumption in Norway. The parametric analysis shows that the well-to-tank emissions for ammonia and green hydrogen production in Norway are expected to be lower than the literature indicates, while for blue and grey hydrogen, the well-to-tank emissions are expected to be in the upper part of the range of emission estimates extracted from the literature. These results are based on assumptions described in chapter 2.1.2 and exclude transport and distribution emissions, as well as the construction of process plants and electrolyzers. Electricity demand for methane reforming and electrolysis are constant in the analysis, but will, in reality, vary depending on the technology and plant size.

The parametric analysis reveals the significant impact of electricity emissions and carbon capture rate on the well-to-tank emissions. Capturing 60 % of the on-site CO_2 emissions in grey hydrogen production will reduce the total well-to-tank emissions by about 50 %, while a capture rate over 90 % will leave blue hydrogen with 70 - 80 % lower greenhouse gas emissions well-to-tank than grey hydrogen. As earlier stated, the origin of electricity is of significant importance for well-to-tank emissions of green hydrogen. Figure 11 reveals a significant gap in well-to-tank emissions between green hydrogen produced with the European electricity mix and the Norwegian electricity mix. In fact, the well-to-tank emissions can be reduced by 95 % if the electricity used for electrolysis origin in renewable energy compared to coal, oil, or gas. The electricity origin also impacts ammonia production emissions, because of the very energy-intensive Haber-Bosch process.

The tank-to-wake emissions reveal significant greenhouse gas emission reduction potential for all three assessed alternative fuels. Excluding well-to-wake emissions, hydrogen and ammonia both offer reductions that will meet the greenhouse gas emission reduction requirements. LNG will reduce the tank-to-wake emissions compared to conventional fuels significantly, but this fuel substitution will not independently offer the emission reductions that are needed. The MariTEAM model also includes separate contributions of each greenhouse gas. When converting CH_4, N_2O, and CO_2 emissions to GWP100 and GWP20 values, the results show that the global warming potential of combustion of LNG and conventional fuels are mainly caused by CO_2 emissions both in a 20- and a 100-year perspective, while N_2O emissions amount to approximately 60% of greenhouse gas emissions from ammonia combustion. The results also show how CH_4 emissions are more important in a GWP20 perspective than a GWP100 perspective.

Adding together well-to-tank emissions from the parametric analysis and tank-to-wake emissions from the MariTEAM model, results in a complete greenhouse gas emission analysis of alternative fuel substitutes well-to-wake. The results reveal drastic emission reduction potential for all alternative fuels compared to conventional fuels. If the alternative fuels are produced using electricity originating in renewable energy and blue hydrogen is produced with a 90% CCS rate, green and blue hydrogen will offer the lowest greenhouse emissions well-to-wake, followed by green ammonia, grey hydrogen, LNG and grey ammonia. All alternative fuels will offer a reduction of greenhouse gas emissions if it is substituted for conventional fuels.

5.2 Implications

Based on the results of the conducted well-to-wake analysis, the Coastal Express can decrease its greenhouse gas emissions and comply with emission reduction requirements by substituting conventional fossil fuels with hydrogen or ammonia. LNG as a fuel alternative can also offer a substantial emission reduction, but the reduction is not sufficient for the emission targets to be achieved. However, mature technology and fuel availability can push LNG to become a short-term solution as a conventional fuel substitute until less emission-intensive fuel technologies mature.

The individual well-to-tank and tank-to-wake analysis illustrates the importance of including emissions from the entire life cycle when assessing the environmental performance of a particular fuel. If only looking at tank-to-wake emissions, i.e., direct fuel emissions, hydrogen will offer a zero-emission fuel alternative. With the challenges the shipping sector is facing, a fuel alternative with this quality should substitute conventional fuels immediately. However, when upstream fuel emissions are taken into consideration, the total fuel emissions increase and other fuels might serve as better alternatives.

Separating out well-to-tank emissions from total fuel emissions enables the calculation of fuel production emissions for specific cases. Technology, production location, and storage facilities all affect the well-to-tank emissions. In this thesis, the influence of electricity emissions and the CCS rate are investigated in particular. The emissions related to electricity are heavily dependent on where the electricity is produced. In Norway, the majority of electricity in the grid originates from renewable energy. This causes very low emissions of electricity consumed domestically. If the fuel production is located in EU instead, the electricity-related emissions will be significantly higher because of the high share of fossil fuels in the electricity grid. Both electrolysis and ammonia synthesis are energy-intensive processes. Emissions related to ammonia and green hydrogen are therefore highly dependent on production location and the origin of the electricity used.

With electricity and water as the only raw materials needed for electrolysis, the location for green hydrogen production is not as limited by raw material supply as other fuels, including grey and blue hydrogen, and LNG. However, the energy-intensive electrolysis process is limited by the electricity supply. A stable electricity supply is important for ensuring sufficient green hydrogen production. Instead of utilizing the electricity grid which can be inefficient, especially along the coastline in the northern part of Norway, green hydrogen can be produced off-grid with a hydropower plant, solar cells, or wind turbines providing electricity.

Consumption of electricity that originates in renewable energy is important for the environmental performance of ammonia production as well. The Haber-Bosch process is an energy-intensive process, and fossil-based electricity will increase well-to-tank emissions significantly. Increased ammonia synthesis due to fuel production without making the Haber-Bosch process cleaner with renewable energy, will only increase the demand for an already very emission-intensive process with high emissions.

CCS is an up-and-coming technology that enables hydrogen to be produced with conventional methods but with drastic emission reduction potentials. Technology improvements have increased the CCS rate from 50 % to 85 - 90 %. It is expected that the rate will increase additionally, and reach 95 - 98 % in few years. The results in this thesis illustrate how an increased CCS rate can reduce the blue hydrogen and blue ammonia emissions substantially. If the CCS rate is increased to 98 %, blue ammonia will also comply with the requirements, along with hydrogen and green ammonia. However, blue hydrogen and blue ammonia will still rely on natural gas production. As it is a fossil resource, natural gas production is not guaranteed for the future. Blue hydrogen and ammonia will therefore most likely not be fuels for the future. As long as grey hydrogen and ammonia are produced, however, implementing CCS in the process will be beneficial for mitigating emissions.

Limited storage possibilities are mentioned as a challenge for all three assessed fuels. Liquefied or compressed fuels require storage facilities of high quality. Storage emissions are difficult to quantify and rarely included in well-to-tank emission studies. It is therefore high uncertainty regarding how storage emissions will affect the well-to-tank emissions and fuel emissions in total. In any case, it is clear that the storage challenges must be addressed in order to make the fuels more mature and attractive.

Despite offering the lowest greenhouse gas emissions, hydrogen and ammonia are in general immature fuel technologies. Both hydrogen and ammonia have been produced for many years but for other applications than as fuels. Implementing hydrogen and ammonia as fuels requires infrastructure and customized ship design. This leads to a chicken or egg problem; fuel substitution is problematic without the necessary fuel infrastructure, but building infrastructure without confirmed end consumers, e.g., shipping companies, is risky. Here, the Coastal Express can play a key role. With a fixed route, the Coastal Express visits the same ports every day. With minimal variations, the vessels are arriving at the ports at the same time every day, and they are staying there for a set amount of time. This makes the Coastal Express a reliable end consumer, which enables the development of infrastructure. With established infrastructure, it would be easier for other ship segments to substitute fossil fuels.

5.3 Thesis limitations

One of the biggest obstacles to accurately analyzing emissions and calculating well-to-wake ratios is the lack of available input data. The well-to-tank analysis presented in this thesis relies on existing literature rather than experienced fuel production data, which means it is a simplified analysis that cannot provide precise upstream fuel emissions. Nevertheless, the well-to-tank analysis does offer valuable insights into the upstream fuel emissions in Norway, based on the assumptions made. The tank-to-wake analysis limitations are conditioned by the MariTEAM model and its properties. For ammonia, a combustion engine is the only technology included in the model. It is therefore not possible to assess tank-to-wake emissions of other ammonia utilization technologies, e.g., fuel cells.

In reality, other factors than greenhouse gas emissions will also influence fuel selection. Availability, price, and technology maturity will likely be more or equally important for decision-makers. An analysis of these factors is not provided in this thesis, but will most likely affect the recommendations of fuel substitutes. For fuel production located in Norway, the study has excluded factors such as electricity availability, grid capacity, locations, or distribution from the assumptions made.

Although the well-to-wake emissions are applied to the Norwegian Coastal Express, the results in this thesis are transferable to other ship segments to a certain extent. The well-to-tank emissions are not specific to a particular ship or ship segment and represent upstream fuel emissions for all applications in Norway besides as fuel. The tank-to-wake emissions are calculated specifically for the Coastal Express, but with emissions per MJ fuel as a functional unit, the emissions will relate to other ship segments to a certain extent.

5.4 Future work

This thesis only offers a comprehensive well-to-wake study of greenhouse gas emission reduction potential for the Norwegian Coastal Express. The focus on greenhouse gases is due to reduction commitments specified regarding greenhouse gas emissions. It is a general agreement that specifies that other emission species, e.g., NO_x and SO_x, also have an impact on climate change. A complete study including all emission species, and their impact on climate change, should be assessed for providing an adequate representation of the fuel alternatives for any decision-making. There is also a need for an understanding of the impact of emissions in a short-term perspective. This thesis offers a brief introduction to the impact of CH_4 in a short-term perspective versus a long-term perspective, but a more extensive short-term approach is necessary with the limited time horizons in the greenhouse gas reduction agreements. Further, the impact of the construction of fuel production plants, as well as impacts related to the renovation or construction of ships that can implement alternative fuels, are not considered in this thesis and should be further studied.

6 Conclusion

Reducing greenhouse gas emissions in the shipping sector is necessary for mitigating climate change. Substituting conventional fossil fuels with low-carbon alternatives is one solution that can reduce shipping emissions in accordance with emission reduction targets. Well-to-wake models provide emission estimates of the entire life cycle of the maritime fuel, from extraction of raw materials (well), through fuel production and combustion in vessel engines (wake).

The objective of this thesis was to investigate if LNG, hydrogen, or ammonia as conventional fuel substitutes could reduce greenhouse gas emissions for the Norwegian Coastal Express in accordance with emission targets. The greenhouse gas emissions were introduced from a well-to-wake perspective, separated into well-to-tank and tank-to-wake emissions. The tank-to-wake emissions were calculated based on data from the MariTEAM model, while a parametric analysis based on present fuel studies gave a comprehensive assessment of well-to-tank emissions for alternative fuels applied in coastal shipping in Norway.

The results show that all assessed alternative fuels can offer a reduction of greenhouse emissions if they are substituted for conventional fuels. Combustion of LNG and ammonia will reduce the tank-to-wake emissions by 25 % and 75 % respectively, while combustion of hydrogen will not emit greenhouse gases at all. When including well-to-tank emissions, the reduction potentials will depend on the fuel production method. Assuming production with electricity originating in renewable energy, hydrogen produced with electrolysis will offer the lowest greenhouse gas emissions well-to-wake, followed by hydrogen produced from natural gas with and without carbon capture and storage implemented in the reforming process. Ammonia can offer significant emission reductions, but emissions reduction targets can only be met if the ammonia is produced with hydrogen originating in electrolysis as feedstock. If CCS is not implemented in the production of hydrogen, ammonia will have higher greenhouse gas emissions than LNG in a well-to-wake perspective.

With its mature technology and availability, LNG can act as a short-term solution as a conventional fuel substitute. The reduction of greenhouse gas emissions will however not be enough as the shipping sector aims to halve its emissions within this decade. Both hydrogen and ammonia can serve as conventional fuel substitutes and reduce shipping emissions in accordance with emission targets. However, limited availability, high costs, and technological immaturity will make this substitution more challenging. With its unique position in Norwegian coastal shipping, the Coastal Express can pursue to fight these challenges and take a giant leap towards a zero-emission shipping sector.

References

[1] A. S. Torper, ‘Hydrogen as a decarbonization solution for the Norwegian coastal express: Estimation of hydrogen demand in selected ports and emission reduction potential by replacing fossil fuels with hydrogen.’, Project work (unpublished), NTNU, Trondheim, Norway, Jan. 2023.

[2] Intergovernmental Panel on Climate Change (IPCC), *AR6 Synthesis Report: Summary for Policymakers Headline Statements*, en. [Online]. Available: https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements/ (visited on 8th Jun. 2023).

[3] International Maritime Organization (IMO), ‘Fourth IMO Greenhouse Gas Study 2020’, London, United Kingdom, Technical Report, 2020. [Online]. Available: https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx.

[4] D. Kramel *et al.*, ‘Global Shipping Emissions from a Well-to-Wake Perspective: The MariTEAM Model’, en, *Environmental Science & Technology*, vol. 55, no. 22, pp. 15 040–15 050, Nov. 2021, ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.1c03937. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.est.1c03937 (visited on 3rd Dec. 2022).

[5] E. Lindstad *et al.*, ‘Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel’, en, *Sustainability*, vol. 12, no. 21, p. 8793, Oct. 2020, ISSN: 2071-1050. DOI: 10.3390/su12218793. [Online]. Available: https://www.mdpi.com/2071-1050/12/21/8793 (visited on 20th Mar. 2023).

[6] C. Fernández-Dacosta *et al.*, ‘Potential and challenges of low-carbon energy options: Comparative assessment of alternative fuels for the transport sector’, en, *Applied Energy*, vol. 236, pp. 590–606, Feb. 2019, ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.11.055. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0306261918317616 (visited on 3rd Nov. 2022).

[7] United Nations Framework Convention on Climate Change (UNFCCC), *The Paris Agreement.* [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement (visited on 8th Jun. 2023).

[8] International Maritime Organization, *Introduction to IMO.* [Online]. Available: https://www.imo.org/en/About/Pages/Default.aspx (visited on 3rd Jan. 2023).

[9] Miljødirektoratet, ‘Klimakur 2030: Tiltak og virkemidler mot 2030’, no, Tech. Rep., Jan. 2020, p. 1197. [Online]. Available: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1625/m1625.pdf.

[10] Klima- og miljødepartementet, ‘Handlingsplan - Regjeringens handlingsplan for grønn skipsfart’, no, Tech. Rep., p. 68.

[11] Miljødirektoratet, *Norges klima- og miljømål*, nb. [Online]. Available: https://miljostatus.miljodirektoratet.no/miljomal/miljomaal/ (visited on 12th Jun. 2023).

[12] Miljødirektoratet, *Skipsfart i EUs kvotesystem*, no. [Online]. Available: https://www.miljodirektoratet.no/ansvarsomrader/klima/klimakvoter/skipsfart-i-eus-kvotesystem/ (visited on 12th Jun. 2023).

[13] Klima- og miljødepartementet and DNV, ‘Barometer for grønn omstilling av skipsfarten 2022’, Tech. Rep. 2022-1359, Rev.4, Sep. 2023.

[14] Statistisk sentralbyrå, *Utslipp til luft*, nb. [Online]. Available: https://www.ssb.no/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft (visited on 12th Dec. 2022).

[15] United States Environmental Protection Agency (US EPA), *Overview of Greenhouse Gases*, en, Overviews and Factsheets, Dec. 2015. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases (visited on 7th Jun. 2023).

[16] M. T. Lund *et al.*, ‘A continued role of short-lived climate forcers under the Shared Socioeconomic Pathways’, English, *Earth System Dynamics*, vol. 11, no. 4, pp. 977–993, Nov. 2020, Publisher: Copernicus GmbH, ISSN: 2190-4979. DOI: 10.5194/esd-11-977-2020. [Online]. Available: https://esd.copernicus.org/articles/11/977/2020/ (visited on 7th Jun. 2023).

[17] United States Environmental Protection Agency, *Nitrogen Oxides Control Regulations*, en, Overviews & Factsheets, [Online]. Available: https://www3.epa.gov/region1/airquality/nox.html (visited on 7th Jun. 2023).

[18] United States Environmental Protection Agency, *Sulfur Dioxide Basics*, en, Overviews and Factsheets, Jun. 2016. [Online]. Available: https://www.epa.gov/so2-pollution/sulfur-dioxide-basics (visited on 7th Jun. 2023).

[19] S. Bengtsson *et al.*, 'A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels', en, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 225, no. 2, pp. 97–110, May 2011, ISSN: 1475-0902, 2041-3084. DOI: 10.1177/1475090211402136. [Online]. Available: http://journals.sagepub.com/doi/10.1177/1475090211402136 (visited on 30th Jan. 2023).

[20] G. Myhre *et al.*, '8 Anthropogenic and Natural Radiative Forcing', en,

[21] P. Balcombe *et al.*, 'How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis', en, *Energy*, vol. 227, p. 120 462, Jul. 2021, ISSN: 03605442. DOI: 10.1016/j.energy.2021.120462. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360544221007118 (visited on 22nd Feb. 2023).

[22] United Nations Framework Convention on Climate Change, *Common metrics*. [Online]. Available: https://unfccc.int/process-and-meetings/transparency-and-reporting/methods-for-climate-change-transparency/common-metrics (visited on 7th Jun. 2023).

[23] J. J. Corbett and J. J. Winebrake, 'Emissions Tradeoffs among Alternative Marine Fuels: Total Fuel Cycle Analysis of Residual Oil, Marine Gas Oil, and Marine Diesel Oil', en, *Journal of the Air & Waste Management Association*, vol. 58, no. 4, pp. 538–542, Apr. 2008, ISSN: 1096-2247, 2162-2906. DOI: 10.3155/1047-3289.58.4.538. [Online]. Available: https://www.tandfonline.com/doi/full/10.3155/1047-3289.58.4.538 (visited on 7th Jun. 2023).

[24] S. Aseel *et al.*, 'Life Cycle Air Emissions and Social Human Health Impact Assessment of Liquified Natural Gas Maritime Transport', en, *Energies*, vol. 14, no. 19, p. 6208, Sep. 2021, ISSN: 1996-1073. DOI: 10.3390/en14196208. [Online]. Available: https://www.mdpi.com/1996-1073/14/19/6208 (visited on 21st Feb. 2023).

[25] A. Valera-Medina *et al.*, 'Ammonia for power', en, *Progress in Energy and Combustion Science*, vol. 69, pp. 63–102, Nov. 2018, ISSN: 03601285. DOI: 10.1016/j.pecs.2018.07.001. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360128517302320 (visited on 10th May 2023).

[26] A. Arteconi *et al.*, 'Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe', en, *Applied Energy*, vol. 87, no. 6, pp. 2005–2013, Jun. 2010, ISSN: 03062619. DOI: 10.1016/j.apenergy.2009.11.012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0306261909004991 (visited on 25th Aug. 2022).

[27] Gasnor, *Drivstoff til skip*. [Online]. Available: https://gasnor.no/produkter/drivstoff-til-skip (visited on 3rd May 2023).

[28] B. Manouchehrinia *et al.*, 'Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada', en, *Energy Reports*, vol. 6, pp. 802–812, Nov. 2020, ISSN: 23524847. DOI: 10.1016/j.egyr.2020.03.016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2352484719312260 (visited on 14th Feb. 2023).

[29] H. Thomson *et al.*, 'Natural gas as a marine fuel', en, *Energy Policy*, vol. 87, pp. 153–167, Dec. 2015, ISSN: 03014215. DOI: 10.1016/j.enpol.2015.08.027. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0301421515300665 (visited on 21st Feb. 2023).

[30] C. Antonini *et al.*, 'Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis', en, *Sustainable Energy & Fuels*, vol. 4, no. 6, pp. 2967–2986, 2020, ISSN: 2398-4902. DOI: 10.1039/D0SE00222D. [Online]. Available: http://xlink.rsc.org/?DOI=D0SE00222D (visited on 18th Apr. 2023).

[31] F. B. Juangsa *et al.*, 'Production of ammonia as potential hydrogen carrier: Review on thermochemical and electrochemical processes', en, *International Journal of Hydrogen Energy*, vol. 46, no. 27, pp. 14 455–14 477, Apr. 2021, ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2021.01.214. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319921004109 (visited on 25th Aug. 2022).

[32] F. Y. Al-Aboosi *et al.*, 'Renewable ammonia as an alternative fuel for the shipping industry', en, *Current Opinion in Chemical Engineering*, vol. 31, p. 100 670, Mar. 2021, ISSN: 22113398. DOI: 10.1016/j.coche.2021.100670. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2211339821000022 (visited on 21st Mar. 2023).

[33] C. Smith *et al.*, 'Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape', en, *Energy & Environmental Science*, vol. 13, no. 2, pp. 331–344, 2020, ISSN: 1754-5692, 1754-5706. DOI: 10.1039/C9EE02873K. [Online]. Available: http://xlink.rsc.org/?DOI=C9EE02873K (visited on 21st Mar. 2023).

[34] International Maritime Organization, *Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines)*. [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/Lifecycle-GHG---carbon-intensity-guidelines.aspx (visited on 7th Jun. 2023).

[35] L. Johansson *et al.*, 'Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution', en, *Atmospheric Environment*, vol. 167, pp. 403–415, Oct. 2017, ISSN: 13522310. DOI: 10.1016/j.atmosenv.2017.08.042. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1352231017305563 (visited on 7th Jun. 2023).

[36] World Nuclear Association, *Heat values of various fuels*. [Online]. Available: https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx (visited on 12th Jun. 2023).

[37] A. Oni *et al.*, 'Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions', en, *Energy Conversion and Management*, vol. 254, p. 115 245, Feb. 2022, ISSN: 01968904. DOI: 10.1016/j.enconman.2022.115245. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0196890422000413 (visited on 18th Apr. 2023).

[38] Nel, *The World's Most Efficient and Reliable Electrolysers*. [Online]. Available: https://acrobat.adobe.com/link/track?uri=urn%3Aaaid%3Ascds%3AUS%3A2e205190-fade-4baa-8672-50afc20379f0&viewer%21megaVerb=group-discover.

[39] K. H. Rouwenhorst *et al.*, 'Islanded ammonia power systems: Technology review & conceptual process design', en, *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109 339, Oct. 2019, ISSN: 13640321. DOI: 10.1016/j.rser.2019.109339. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032119305477 (visited on 12th Jun. 2023).

[40] X. Liu *et al.*, 'Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products', en, *Green Chemistry*, vol. 22, no. 17, pp. 5751–5761, 2020, ISSN: 1463-9262, 1463-9270. DOI: 10.1039/D0GC02301A. [Online]. Available: http://xlink.rsc.org/?DOI=D0GC02301A (visited on 21st Mar. 2023).

[41] Universitetet i Oslo, *Periodesystemet*, no. [Online]. Available: https://www.periodesystemet.no/ (visited on 12th Jun. 2023).

[42] R. W. Howarth *et al.*, 'What Influence Will Switching to Natural Gas Have on Climate? User guide for natural gas leakage rate modeling tool', en, *Climatic Change*, vol. 106, no. 4, pp. 679–690, Jun. 2011, ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-011-0061-5. [Online]. Available: http://link.springer.com/10.1007/s10584-011-0061-5 (visited on 12th Jun. 2023).

[43] E. Cetinkaya *et al.*, 'Life cycle assessment of various hydrogen production methods', en, *International Journal of Hydrogen Energy*, vol. 37, no. 3, pp. 2071–2080, Feb. 2012, ISSN: 03603199. DOI: 10.1016/j.ijhydene.2011.10.064. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S036031991102430X (visited on 3rd Nov. 2022).

[44] S. Schloemer *et al.*, 'Annex III: Technology-specific cost and performance parameters', English, in *Climate Change 2014: Mitigation of Climate Change*, O. Edenhofer *et al.*, Eds., United Kingdom: Cambridge University Press, 2014, pp. 1329–1356, ISBN: 978-1-107-65481-5.

[45] Enerdata, *2050 Projections for CO2 Intensity of Electricity Generation*, en. [Online]. Available: https://eneroutlook.enerdata.net/forecast-world-co2-intensity-of-electricity-generation.html (visited on 12th Jun. 2023).

[46] N. Kjerstad, *AIS*, no, Nov. 2022. [Online]. Available: http://snl.no/AIS (visited on 3rd Jan. 2023).

[47] G. Myhre *et al.*, 'Anthropogenic and Natural Radiative Forcing Supplementary Material', in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. Stocker *et al.*, Eds., IPCC, 2013. [Online]. Available: https://www.climatechange2013.org%20and%20https://www.ipcc.ch.

[48] Y. Khojasteh Salkuyeh *et al.*, 'Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies', en, *International Journal of Hydrogen Energy*, vol. 42, no. 30, pp. 18 894–18 909, Jul. 2017, ISSN: 03603199. DOI: 10.1016/j.ijhydene.2017.05.219. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360319917322036 (visited on 19th Apr. 2023).

[49] O. Kanz *et al.*, 'Review and Harmonization of the Life-Cycle Global Warming Impact of PV-Powered Hydrogen Production by Electrolysis', *Frontiers in Electronics*, vol. 2, 2021, ISSN: 2673-5857. [Online]. Available: https://www.frontiersin.org/articles/10.3389/felec.2021.711103 (visited on 3rd Nov. 2022).

[50] M. Aziz *et al.*, 'Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization', en, *Energies*, vol. 13, no. 12, p. 3062, Jan. 2020, Number: 12 Publisher: Multidisciplinary Digital Publishing Institute, ISSN: 1996-1073. DOI: 10.3390/en13123062. [Online]. Available: https://www.mdpi.com/1996-1073/13/12/3062 (visited on 25th Aug. 2022).

[51] Havila Kystruten, *Kystrutens historie.* [Online]. Available: https://www.havilavoyages.com/nb/om-havila/kystrutens-historie (visited on 12th Jun. 2023).

[52] Samferdselsdepartementet, *Kystruteavtale for perioden 2021-2030*, no, Redaksjonellartikkel, Publisher: regjeringen.no, Nov. 2022. [Online]. Available: https://www.regjeringen.no/no/tema/transport-og-kommunikasjon/kollektivtransport/kystruten/kystruteavtale-for-perioden-2021-2030/id2517842/ (visited on 23rd Dec. 2022).

[53] *MarineTraffic: Global Ship Tracking Intelligence — AIS Marine Traffic.* [Online]. Available: https://www.marinetraffic.com/en/ais/home/centerx:11.3/centery:66.8/zoom:4 (visited on 23rd Dec. 2022).

[54] Hurtigruten Coastal AS, *Skip med sjel*, no. [Online]. Available: https://www.hurtigruten.no/skip/ (visited on 8th Jun. 2023).

[55] P. Jaramillo *et al.*, 'Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation', en, *Environmental Science & Technology*, vol. 41, no. 17, pp. 6290–6296, Sep. 2007, ISSN: 0013-936X, 1520-5851. DOI: 10.1021/es063031o. [Online]. Available: https://pubs.acs.org/doi/10.1021/es063031o (visited on 14th Feb. 2023).

[56] T. Okamura *et al.*, 'Future forecast for life-cycle greenhouse gas emissions of LNG and city gas 13A', en, *Applied Energy*, vol. 84, no. 11, pp. 1136–1149, Nov. 2007, ISSN: 03062619. DOI: 10.1016/j.apenergy.2007.05.005. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0306261907000505 (visited on 14th Feb. 2023).

[57] R. Verbeek *et al.*, 'Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands', en, Delft, The Netherlands, Tech. Rep. TNO-RPT-2011-00166, Jan. 2011, p. 48. [Online]. Available: https://www.schonescheepvaart.nl/downloads/rapporten/doc_1370359071.pdf.

[58] S. Hwang *et al.*, 'Life Cycle Assessment of LNG Fueled Vessel in Domestic Services', en, *Journal of Marine Science and Engineering*, vol. 7, no. 10, p. 359, Oct. 2019, ISSN: 2077-1312. DOI: 10.3390/jmse7100359. [Online]. Available: https://www.mdpi.com/2077-1312/7/10/359 (visited on 22nd Feb. 2023).

[59] H. Jang *et al.*, ‘Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel’, en, *Applied Energy*, vol. 292, p. 116 869, Jun. 2021, ISSN: 03062619. DOI: 10.1016/j.apenergy.2021.116869. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0306261921003597 (visited on 22nd Feb. 2023).

[60] C. Tagliaferri *et al.*, ‘Liquefied natural gas for the UK: A life cycle assessment’, en, *The International Journal of Life Cycle Assessment*, vol. 22, no. 12, pp. 1944–1956, Dec. 2017, ISSN: 0948-3349, 1614-7502. DOI: 10.1007/s11367-017-1285-z. [Online]. Available: http://link.springer.com/10.1007/s11367-017-1285-z (visited on 22nd Feb. 2023).

[61] S. Brynolf *et al.*, ‘Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol’, en, *Journal of Cleaner Production*, vol. 74, pp. 86–95, Jul. 2014, ISSN: 09596526. DOI: 10.1016/j.jclepro.2014.03.052. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652614002832 (visited on 30th Jan. 2023).

[62] Hydrogen Council, ‘Hydrogen decarbonization pathways. Part 2 – Potential Supply Scenarios’, Tech. Rep., Jan. 2021. [Online]. Available: https://hydrogencouncil.com/en/hydrogen-decarbonization-pathways/.

[63] S. Chugh *et al.*, ‘Comparing prospective hydrogen pathways with conventional fuels and grid electricity in India through well-to-tank assessment’, en, *International Journal of Hydrogen Energy*, vol. 47, no. 41, pp. 18 194–18 207, May 2022, ISSN: 03603199. DOI: 10.1016/j.ijhydene.2022.03.280. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360319922014513 (visited on 20th Mar. 2023).

[64] A. J. Boero *et al.*, ‘Environmental Life Cycle Assessment of Ammonia-Based Electricity’, en, *Energies*, vol. 14, no. 20, p. 6721, Oct. 2021, ISSN: 1996-1073. DOI: 10.3390/en14206721. [Online]. Available: https://www.mdpi.com/1996-1073/14/20/6721 (visited on 21st Mar. 2023).

[65] D.-A. Chisalita *et al.*, ‘Environmental evaluation of european ammonia production considering various hydrogen supply chains’, en, *Renewable and Sustainable Energy Reviews*, vol. 130, p. 109 964, Sep. 2020, ISSN: 13640321. DOI: 10.1016/j.rser.2020.109964. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032120302550 (visited on 25th Aug. 2022).

[66] S. Ghavam *et al.*, ‘Sustainable Ammonia Production Processes’, en, *Frontiers in Energy Research*, vol. 9, p. 580 808, Mar. 2021, ISSN: 2296-598X. DOI: 10.3389/fenrg.2021.580808. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fenrg.2021.580808/full (visited on 25th Aug. 2022).

[67] H. L. Raadal *et al.*, ‘Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power’, en, *Renewable and Sustainable Energy Reviews*, vol. 15, no. 7, pp. 3417–3422, Sep. 2011, ISSN: 13640321. DOI: 10.1016/j.rser.2011.05.001. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032111001924 (visited on 12th Jun. 2023).

[68] Norges vassdrags- og energidirektorat (NVE), *Hvor kommer strømmen fra?*, no, May 2023. [Online]. Available: https://www.nve.no/energi/energisystem/kraftproduksjon/hvor-kommer-stroemmen-fra/ (visited on 12th Jun. 2023).

[69] NVE, *Lavt klimagassutslipp knyttet til norsk strømforbruk i 2020*, no, Feb. 2021. [Online]. Available: https://www.nve.no/nytt-fra-nve/nyheter-energi/lavt-klimagassutslipp-knyttet-til-norsk-stromforbruk-i-2020/ (visited on 12th Jun. 2023).

A Code for parametric well-to-tank analysis

```python
import pandas as pd
import numpy as np
from pathlib import Path

#PARAMETERS
#Energy content of natural gas, NG
NG_ENERGY_CONTENT = 50 #MJ/kg NG
#Energy content of hydrogen, H2
H2_ENERGY_CONTENT = 120 #MJ/kg H2
#Energy content of ammonia, NH3
NH3_ENERGY_CONTENT = 18.8 #MJ/kg
#reforming electricity demand
REFORMING_ELECTRICITY_DEMAND = 2.3 #kWh/kg H2
#Electrolyzer electricity demand
ELECTROLYZER_ELECTRICITY_DEMAND = 55 #kWh/kgH2
#HB+ASU electricity demand
HB_ASU_ELECTRICITY_DEMAND = 0.75 #kWh/kg NH3
#Natural gas feedstock per kg hydrogen
NG_FEEDSTOCK = 2.5 #kg NG/kg H2
#Hydrogen feedstock per kg ammonia
H2_DEMAND = 178/1000 #kg/kg NH3
#Nitrogen feedstock per kg ammonia
N2_DEMAND = 822/1000 #kg/kg NH3
#Molar masses
MOL_CO2 = 44 #g/mol
MOL_CH4 = 16 #g/mol
MOL_C = 12 #g/mol

#Variables
#Thermal efficiency
thermal_efficiency = 0.75 #75%
#Methane leakage
METHANE_LEAKAGE = 0.001 #0.1%
#Hydrogen storage
H2_STORAGE = 1.42 #gCO2eq/MJ
#Upstream NG emissions
NG_UPSTREAM_EMISSIONS = 12 #gCO2/MJ LNG
#Carbon capture rate
cc = 0.90 #95%
#Electricity emissions
reforming_electricity_emissions = 19 #gCO2eq/kWh
electrolyzis_electricity_emissions = 19 #gCO2eq/kWh
hb_asu_grey_electricity_emissions = 19 #gCO2eq/kWh
hb_asu_blue_electricity_emissions = 19 #gCO2eq/kWh
hb_asu_green_electricity_emissions = 19 #gCO2eq/kWh

#Direct emissions in SMR/ATR
REFORMING_EMISSIONS = ((NG_FEEDSTOCK * (MOL_C/MOL_CH4) * (MOL_CO2/MOL_C) * 1000
#Hydrogen upstream emissions
H2_UPSTREAM = (NG_FEEDSTOCK*NG_ENERGY_CONTENT*NG_UPSTREAM_EMISSIONS *(1+METHANE_LEAKAGE))

def get_h2_grey(reforming_electricity_emissions):
    h2_electricity = REFORMING_ELECTRICITY_DEMAND*
    ↪   reforming_electricity_emissions/H2_ENERGY_CONTENT
    H2_GREY_UPSTREAM = H2_UPSTREAM/H2_ENERGY_CONTENT
    ON_SITE_EMISSIONS = REFORMING_EMISSIONS/H2_ENERGY_CONTENT
    return H2_GREY_UPSTREAM + h2_electricity + H2_STORAGE + ON_SITE_EMISSIONS

def get_h2_blue(cc, reforming_electricity_emissions):
```

```
    h2_blue_electricity = REFORMING_ELECTRICITY_DEMAND*
    ↪  reforming_electricity_emissions/H2_ENERGY_CONTENT
    H2_UPSTREAM_BLUE = ((NG_FEEDSTOCK*NG_ENERGY_CONTENT*NG_UPSTREAM_EMISSIONS *
    ↪  (1+METHANE_LEAKAGE*27))/H2_ENERGY_CONTENT)
    ON_SITE_EMISSIONS = REFORMING_EMISSIONS * (1-cc) / H2_ENERGY_CONTENT
    return H2_UPSTREAM_BLUE + h2_blue_electricity + H2_STORAGE + ON_SITE_EMISSIONS

def get_h2_green(electrolyzis_electricity_emissions):
    return ((ELECTROLYZER_ELECTRICITY_DEMAND * electrolyzis_electricity_emissions)/
    ↪  H2_ENERGY_CONTENT) + H2_STORAGE

def get_nh3_grey(reforming_electricity_emissions, hb_asu_grey_electricity_emissions):
    h2_electricity = REFORMING_ELECTRICITY_DEMAND* reforming_electricity_emissions /
    ↪  NH3_ENERGY_CONTENT
    nh3_synthesis = (HB_ASU_ELECTRICITY_DEMAND * hb_asu_grey_electricity_emissions) /
    ↪  NH3_ENERGY_CONTENT
    NH3_UPSTREAM = (REFORMING_EMISSIONS + H2_UPSTREAM) * H2_DEMAND / NH3_ENERGY_CONTENT
    return h2_electricity + NH3_UPSTREAM + nh3_synthesis + 0.8*H2_STORAGE

def get_nh3_blue(cc, hb_asu_blue_electricity_emissions, reforming_electricity_emissions):
    h2_electricity = REFORMING_ELECTRICITY_DEMAND* reforming_electricity_emissions /
    ↪  NH3_ENERGY_CONTENT
    nh3_synthesis = (HB_ASU_ELECTRICITY_DEMAND * hb_asu_blue_electricity_emissions) /
    ↪  NH3_ENERGY_CONTENT
    NH3_UPSTREAM = (REFORMING_EMISSIONS* (1-cc) + H2_UPSTREAM) * H2_DEMAND /
    ↪  NH3_ENERGY_CONTENT
    return h2_electricity + NH3_UPSTREAM  + nh3_synthesis + 0.8*H2_STORAGE

def get_nh3_green(hb_asu_green_electricity_emissions, electrolyzis_electricity_emissions):
    nh3_synthesis = HB_ASU_ELECTRICITY_DEMAND * hb_asu_green_electricity_emissions /
    ↪  NH3_ENERGY_CONTENT
    H2_NH3_GREEN = (ELECTROLYZER_ELECTRICITY_DEMAND * electrolyzis_electricity_emissions *
    ↪  H2_DEMAND)/ NH3_ENERGY_CONTENT
    return nh3_synthesis + H2_NH3_GREEN + 0.8*H2_STORAGE

#ATR/SMR electricity emissions
reforming_electricity_emissions_cases = [19, 19, 19, 12, 19, 200, 300] #gCO2/kWh
#Grey NH3 emissions
hb_asu_grey_electricity_emissions_cases = [19, 19, 19, 12, 19, 200, 300] #gCO2/kWh
# Green NH3
hb_asu_green_electricity_emissions_cases = [19, 19, 19, 12, 19, 200, 300]
# Blue NH3
hb_asu_blue_electricity_emissions_cases = [19, 19, 19, 12, 19, 200, 300]
# Green H2
electrolyzis_electricity_emissions_cases = [19, 19, 19, 12, 19, 200, 300]
cc_cases = [.60,  .90,  .98,  .90,  .90,  .90,  .90]


cases = {}
for i in range(len(cc_cases)):
    cases[i] =  {
        #HB+ASU electricity emissions
        "hb_asu_grey_electricity_emissions": hb_asu_grey_electricity_emissions_cases[i],

        #reforming electricity emissions
        "reforming_electricity_emissions": reforming_electricity_emissions_cases[i],

        # Green NH3
        "hb_asu_green_electricity_emissions": hb_asu_green_electricity_emissions_cases[i],

        # Blue NH3
        "hb_asu_blue_electricity_emissions": hb_asu_green_electricity_emissions_cases[i],

```

```
        # Green H2
        "electrolyzis_electricity_emissions": electrolyzis_electricity_emissions_cases[i],

        #Carbon capture rate
        "cc": cc_cases[i]
    }

cases_emissions = defaultdict(dict)
for idx, (case_num, case) in enumerate(cases.items(), start=1):
    cases_emissions[idx]["lng"] = NG_UPSTREAM_EMISSIONS
    cases_emissions[idx]["h2_grey"] = get_h2_grey(case["reforming_electricity_emissions"])
    #h2_blue_total_mj, blue_h2_total_kg =
    cases_emissions[idx]["h2_blue"] = get_h2_blue(case["cc"],
    ↪   case["reforming_electricity_emissions"])
    cases_emissions[idx]["h2_green"] =
    ↪   get_h2_green(case["electrolyzis_electricity_emissions"])
    cases_emissions[idx]["nh3_grey"] =
    ↪   get_nh3_grey(case["hb_asu_grey_electricity_emissions"],
    ↪   case["reforming_electricity_emissions"])
    cases_emissions[idx]["nh3_blue"] = get_nh3_blue(case["cc"],
    ↪   case["hb_asu_blue_electricity_emissions"],
    ↪   case["reforming_electricity_emissions"])
    cases_emissions[idx]["nh3_green"] =
    ↪   get_nh3_green(case["hb_asu_green_electricity_emissions"],
    ↪   case["electrolyzis_electricity_emissions"])

```

B Code for tank-to-wake analysis

```python
import pandas as pd
from pathlib import Path
import matplotlib.pyplot as plt

FUEL_TYPES = ["hfo", "lng_hp", "mgo", "ammonia", "H2"]

#Importing MariTEAM results and sorting out unrelevant ships
ttw_base_path = Path("../MariTEAM results/NEW_hurtigruten")
all_ship_codes = set([path.stem.split("_")[0] for path in sorted(ttw_base_path.iterdir())])
BLACKLIST_SHIP_CODES = ["258157000", "259210000"]
relevant_ttw_paths = [path for path in ttw_base_path.iterdir() if path.stem.split("_")[0] in (all_ship_codes - set(BLACKLIST_SHIP_CODES))]
paths_per_fuel = {fuel: [path for path in relevant_ttw_paths if fuel in path.stem] for fuel in FUEL_TYPES}

#Defining GWP100 and GWP20 metric values
gwp_100_factors = {
    "CO2": 1,
    "CH4": 28.5,
    "N2O": 264.8,
}
gwp_100_factors_series = pd.Series(gwp_100_factors, name="gwp_100")
gwp_20_factors = {
    "CO2": 1,
    "CH4": 83.9,
    "N2O": 263.7,
}
gwp_20_factors_series = pd.Series(gwp_20_factors, name="gwp_20")

emission_cols = ['CO2', 'CH4', 'N2O', 'NMVOC', 'SO2', 'SO4', 'NOx', 'CO', 'OC', 'EC', 'BC']

#Calculating tank-to-wake emissions
def get_co2_eq_ttw(ship_paths: list, co2_eq_factors: pd.Series, emission_cols=emission_cols) -> pd.DataFrame:
    """
    General method to get the CO2eq TTW per ship given list of paths to ships for a type of fuel.

    co2_eq_factors: is the conversion rate per emission species, e.g. GWP_100, as a pd.Series

    returns: pd.DataFrame
            A pd.DataFrame containing the average CO2eq/MJ based on 1 year of data per ship, per GHG

    """
    all_data_points = pd.concat([pd.read_csv(path, index_col=0) for path in ship_paths])
    #kws2mj = 3.6 / 3600
    ws2mj = 1e-6
    # Convert main engine power from kw or w to MJ, based on the time spent
    all_data_points.loc[:,"main_engine_power_mj"] = (all_data_points.loc[:,"main_engine_power_kw"] * all_data_points.loc[:,"delta_time_s"]) * ws2mj

    # For each ship, calculate g/MJ for each emission species based on each data point
    # Sum the adjusted data points together for each spicies
    all_delta_emissions_adjusted = (all_data_points
                                    .groupby("mmsi")
```

```
                                    .apply(lambda group: group[emission_cols]
                                           .div(group["main_engine_power_mj"],
                                           ↪   axis="index")
                                           .median()
                                          )
                                   )

    # Convert emission species to CO2eq given the convertion factors, for each ship
    # NB: The factors must line up with the species columns in the dataframe

    co2eqs = all_delta_emissions_adjusted * co2_eq_factors

    # Total CO2eqs per ship
    return co2eqs#.sum(axis=1).rename(co2_eq_factors.name).to_frame()

get_co2_eq_ttw(paths_per_fuel["lng_hp"], gwp_100_factors_series).iloc[:, :3]

get_co2_eq_ttw(paths_per_fuel["H2"], gwp_100_factors_series).iloc[:, :3]

get_co2_eq_ttw(paths_per_fuel["ammonia"], gwp_100_factors_series).iloc[:, :3]

#Emissions per fuel type
fuel_name_map = {"H2": "H2", "ammonia": "NH3", "hfo": "HFO", "lng_hp": "LNG", "mgo":
↪   "MGO"}

%%time
# Iterate over each fuel's corresponding emission files and calculate TTW
fuel2emissions_gwp_100 = {fuel_name_map[fuel]: get_co2_eq_ttw(paths,
                                               gwp_100_factors_series,
                                               emission_cols=emission_cols)
                          for fuel, paths in paths_per_fuel.items()}

fuels, gwp_100_emissions = zip(*({fuel: ttw.sum(axis=1) for fuel, ttw in
↪   fuel2emissions_gwp_100.items()}).items())

# Merge all GWP_100 values for each fuel
all_gwp_100_emissions = pd.concat(gwp_100_emissions, axis=1, keys=fuels)#.droplevel(1,
↪   axis=1)

#Contribution of each GHG
fuel_by_emissions = pd.concat(fuel2emissions_gwp_100.values(),
↪   keys=fuel2emissions_gwp_100.keys())[["CO2", "CH4", "N2O"]]

#Repeat for GWP20
%%time
# Iterate over each fuel's corresponding emission files and calculate TTW for GWP20
fuel2emissions_gwp_20 = {fuel_name_map[fuel]: get_co2_eq_ttw(paths,
                                               gwp_20_factors_series,
                                               emission_cols=emission_cols)
                          for fuel, paths in paths_per_fuel.items()}

fuel_by_emissions_gwp_20 = pd.concat(fuel2emissions_gwp_20.values(),
↪   keys=fuel2emissions_gwp_20.keys())[["CO2", "CH4", "N2O"]]
```

C Metric values of GWP20 and GWP100

Metric values of GWP20 and GWP100 for CO_2, N_2O and CH_4. The values are retrieved from the Supplementary Material in IPCC 5th Assessment Report [47].

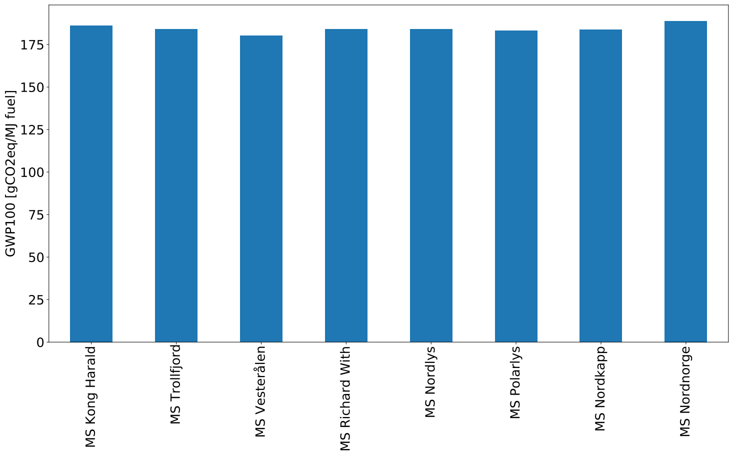
Metric values of GWP20 and GWP100 for CO_2, N_2O and CH_4.

Emissions species	**GWP20**	**GWP100**
CO_2	1	1
CH_4	83.9	28.5
N_2O	263.7	264.8

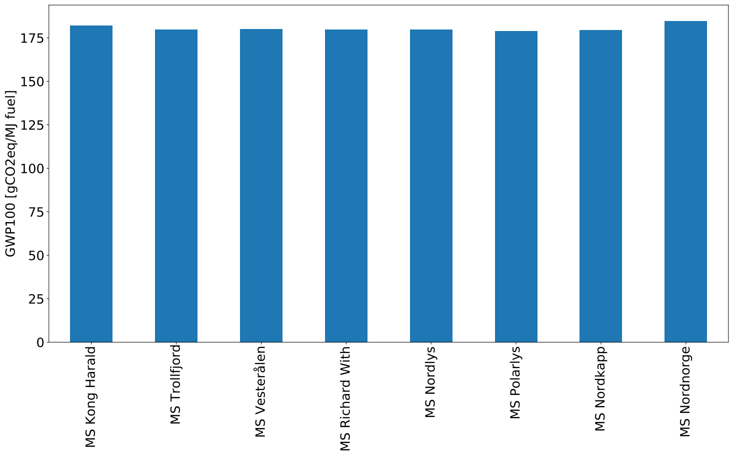
D Tank-to-wake emissions per ship

Tank-to-wake emissions for each ship in the ship segment. The emissions are calculated with the MariTEAM model.

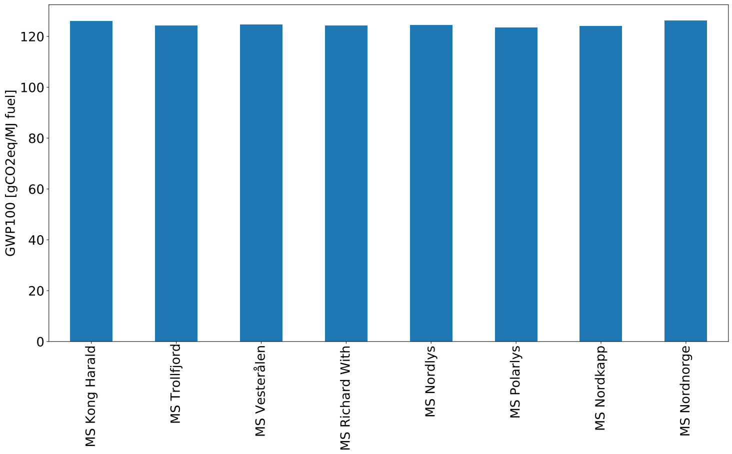
Tank-to-wake emissions with heavy fuel oil (HFO) as fuel:



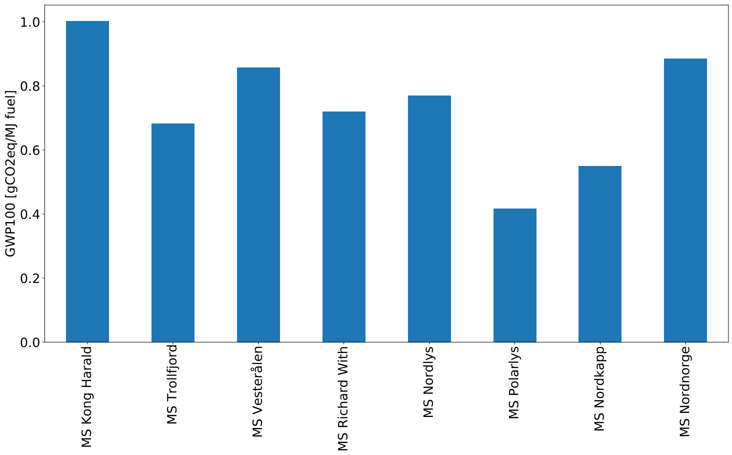
Tank-to-wake emissions with marine gas oil (MGO) as fuel:



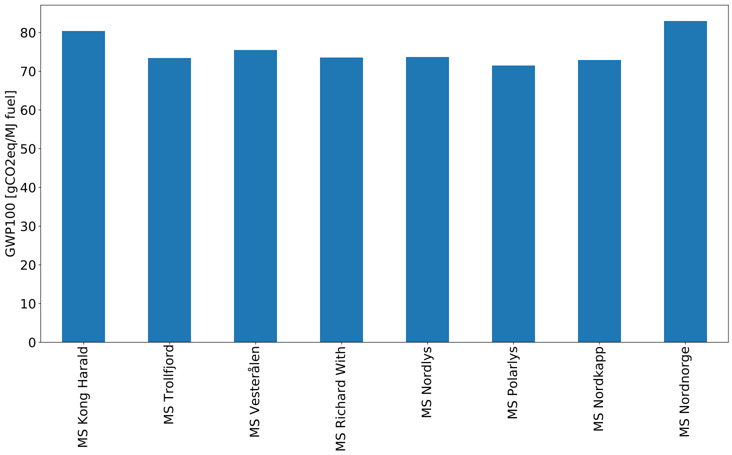
Tank-to-wake emissions with liquefied natural gas (LNG) as fuel:



Tank-to-wake emissions with hydrogen as fuel:



Tank-to-wake emissions with ammonia as fuel:



NTNU

Norwegian University of
Science and Technology