Assessing the financial impact of using alternative fuels and speed reduction on chemical tankers to comply with emission reduction targets

MT.21/22.012.M.

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by

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Preface

In 2015 I started the bachelor Marine Technology in Delft and now six and a half year later I am finishing my studies in this field. From day one I have enjoyed my studies and student life in Delft which both enabled me to develop myself. This thesis is a result of these six years, in which I developed a specific interest in the economics behind shipping. As the world is shifting towards a greener economy, the shipping industry has undoubtedly arrived at a interesting point in its history. It will need to develop new solutions and use cleaner energy sources to reduce its footprint on the earth. However as big as it might feel, it is not the first time that shipping made such a large great technological shift. From hand powered vessels, shipping first shifted to sailing, then to coal, then to fuel oils and now again to new sources. As I experienced in this study, the economics behind this shift to new fuels is a complex subject with many interdependencies and a great deal of factors to be considered. With this study I hope to have added a bit of knowledge to this field. This report that you find before you, is a part of my master thesis, which is the final deliverable for the Master of Science degree in Marine Technology at the Delft University of Technology. I specialised within the masters on the track ship design.

Getting to this point has been a great learning experience and I would like to thank several people that helped me getting here. First of all, the chair of my study, Austin Kana. I think he did great supervising my thesis, always very considerate, interested and critical during the entire process.

Secondly, I want to thank Robert Hekkenberg. Robert started as my supervisor but made a switch to a new job outside the TU Delft during my thesis after which Austin Kana took over from him. Robert has been of great support during the first part of my thesis.

Thirdly, I want to thank Niels de Vries which was my supervisor at C-Job and enabled me to do research at a fantastic company. Thank you for all the time you spend on our weekly meetings, reviewing documents and helping me. I also want to thank all other people at C-Job.

Finally I want to thank Björn van de Weerdhof. I consider the few meeting we had of significant importance to my thesis.

E.E. Mink van der Molen
Delft, January 2021

Definitions

Conventional fuel
Fossil fuels that are presently commonly in use in the maritime industry, i.e. MGO and HFO.

Alternative fuel
Fuels that are presently not commonly in use maritime industry such as methanol, hydrogen, ammonia. In other words all fuels except variants of HFO and MGO.

Renewable fuel
Fuels that are produced using a sustainable production method, this can be bio-fuel or synthetically produced fuel from renewable electricity.

E-fuel
A fuel produced synthetically from renewable electricity.

Summary

As the world is slowly shifting towards a more sustainable economy, the shipping industry has also experienced increased pressure to reduce emissions. To achieve such emission reductions, regulation could be implemented in the future by governmental bodies. Such regulation can take the shape of direct emission reduction requirements or indirect measures such as a carbon tax. One of the ship types that will also experience the influence of such regulation are chemical tankers. To comply with regulation, several measures can be taken. First of all, the efficiency the vessel can be improved. Secondly the operational speed of a tanker can be reduced. Finally tankers could use alternative fuels. This can be a fossil alternative fuel such as LNG or a renewable fuel. There are many candidates that could be used as renewable fuel on vessels, all having specific challenges and upsides.

While such measures can be used to reduce emission, the present use of especially renewable fuels is negligible due to the high cost. However if confronted with new regulation, ship operators will be forced to turn to these measures. It is then important for shipowners to be able to select the most promising measure or alternative fuel for their specific operations and vessel.

The research objective of this thesis is therefore to develop a models that can help to gain better insight into the financial impact of using alternative fuels and speed reduction to comply with emission reduction regulation. By applying these models on a broad range of vessels and scenario's, trends could then be found. The main research question is: *What is the financial impact of using alternative fuels and speed reductions on a chemical tanker to comply with decarbonization regulation, considering various carbon tax scenario's?*

To answer this question, first research scenarios were generated. Parameters that are varied for the different scenarios are: the decarbonization pathway, the emission reduction strategies, the carbon tax, and the fuel prices. Fuels included are MGO, ammonia, methanol and methane(LNG). Only synthetic fuels (e-fuel) are included as renewable fuel. Next the life-cycle-emissions of the fossil and renewable versions of fuels were analysed. Emissions are measured on a life cycle bases to avoid shifting emission from the tank-to-wake to the well-to-tank phase. Next a model is developed to predict future fuel prices of renewable fuels. It was found that e-ammonia is expected to have the lowest production cost, while higher cost are expected for e-methanol and e-methane. For all fuels, production cost are expected to decrease significantly between 2025 and 2050.

Next models were developed to analyse the scenario's. For all scenarios, a range of vessels was analysed. Vessel parameters that were varied are: deadweight, trade distance and design speed. Based on the results from these models the following statements can be made:

- For a chemical tanker that is required to operate with a 70% lower emission intensity during its entire lifetime, the model determined what is the best renewable fuel to mix in with MGO. No speed reduction was used in this case. The model found that renewable ammonia is the most cost-effective solution. This conclusion showed limited sensitivity to vessel size, design speed, trade distance, carbon price or renewable fuel prices.
- For a chemical tanker that is required to comply with increasingly stricter IMO emission intensity goals on a yearly bases, the model determined what is the best alternative fuel. The vessel then runs on a combination of renewable and fossil alternative fuel that is adjusted annually to comply with the emission reduction goal. No speed reduction was used on this case. It was found that for this case, ammonia is the most cost-effective alternative fuel. This conclusion showed limited sensitivity to vessel size, design speed, trade distance, carbon price or renewable fuel prices.
- For a chemical tanker that is required to comply with increasingly stricter IMO emission intensity goals on a yearly bases, the model determined what is the best alternative fuel when the vessel is also allowed to reduce its speed. The vessel then runs on a combination of renewable and fossil alternative fuel that

> is adjusted annually to comply with the emission reduction goal. This scenario was only analysed for a large scale tanker. The optimal fuel choice showed significant sensitivity to the freight rate. When the freight rate is low, methane is the best alternative fuel. When the freight rate is high, ammonia is the best alternative fuel. When the methane slip is reduced to levels that will achievable in several years, the optimal fuel choice was methane for both freight rates. Furthermore it was found that the optimal speed was lower than the reference speed for all scenarios and freight rates.

Furthermore it was found that in almost all scenarios, the cost of shipping will increase significantly in both absolute cost as well when measured relative to the reference cases including carbon tax. Only scenarios with a combination of high carbon taxes and low renewable fuel prices resulted in a very limited increase or small decrease in cost relative to the reference case including carbon tax.

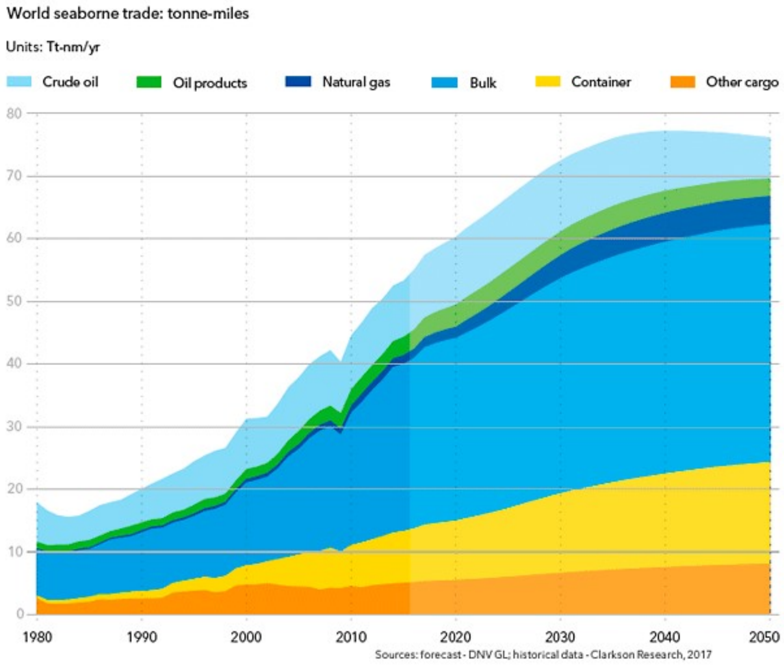
This research and constructed models can be used as a tool to evaluate financial impact of complying with possible emission regulation. However, used values are based on sources and their corresponding assumptions. These can change significantly in the future, changing the outcome of the model.

Contents

1

Introduction

Maritime shipping presently accounts for most of the global ton-miles worldwide, especially over long distances and due to worldwide economical growth, the global demand for freight transport will experience a significant growth over the coming decades. DNV GL predicts that seaborne trade will increase in all trade segments except crude oil and oil products and will grow by 39% measured in transported tonnes between 2016 and 2030, and a further 2% between 2030 and 2050[30]. In other words, demand for shipping in tonne-miles will will peak between 2030 and 2040 after which demand will stabilise. These dynamics can be seen in figure 1.1[28]. This increasing amount of shipping demand will result in more emissions while in 2018 ship-



Sources: forecast - DNV GL; historical data - Clarkson Research, 2017

Average annual growth rate in %	2010-2016	2016-2030	2030-2050
Crude oil	1.8	1.2	-2.7
Oil products	2.7	1.5	-1.5
Natural gas	4.1	6.8	1.0
Bulk	4.4	1.7	0.5
Container	4.5	2.8	1.2
Other cargo	4.5	2.8	1.0
Average	3.7	2.0	0.2

Figure 1.1: Predicted global sea trade and growth[28].

ping emissions already accounted for 2.89% of global anthropogenic greenhouse gas emissions.

Regulation

The shipping industry has meanwhile experienced increased pressure to reduce these emissions. To create the needed incentive more regulation could be implemented in the future by governmental bodies. The International Maritime Organisation (IMO) has adopted an ambitious long-term strategy with the aim to reduce harmful GHG emissions with at least 50% by 2050 compared to 2008. Furthermore the IMO aims to reduce the carbon intensity (CO_2 per tonne-mile) of the shipping industry with more than 40% by 2030 and by more than 70% by 2050 as can be seen in figure 1.2. Presently these goals have not been translated into regulation, so vessels do not have to comply with these goals, however in the future further regulation could be implemented forcing vessels to reduce their emissions.

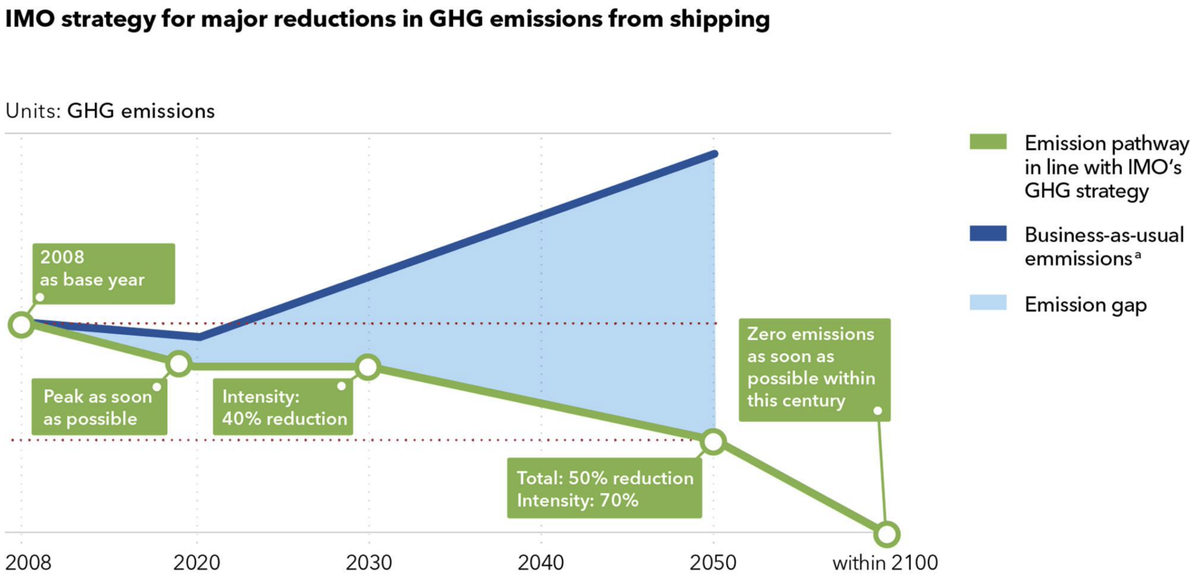


Figure 1.2: Visualisation of the IMO ambitions[29]

Chemical tanker market

One of the shipping markets that could experience significant impact from such a shift to a more sustainable world economy and maritime industry is the chemical tanker market. Firstly because the demand within the tanker market could shift away from the transport of fossil fuels. According to Wartsila, the demand for oil tankers might drop by half in the most extreme reduction scenario and gas demand could drop by a quarter[6]. However the energy transition could also be positive for chemical tankers because clean energy sources are not spread fairly around the world which could boost the demand for transport of renewable fuels to area's lacking the capability to produce this energy[6]. Secondly the tanker market will feel impact from the possible regulation as discussed earlier, which will require emission reductions.

Possible Measures

If tankers want to reduce emissions and meet these carbon reduction targets set by the IMO for 2050, fundamental different technologies and operational changes will have to be adopted. The maritime industry has been discussing potential emission reducing solutions for many years and several possible types of measures can be distinguished that could reduce shipping emissions[26].

First of all the emissions of tanker can be reduced by improving the design of the tanker and increasing the efficiency. The IMO aims to enforce such improvement through the implementation of an energy efficiency design index (EEDI) for new ships. The purpose of the EEDI for new build ships is to promote the use of more energy efficient equipment and engines. The EEDI wants to achieve this goal by requiring a minimum energy efficiency level per tonne mile. The IMO intents to tighten the required EEDI incrementally every five years and by doing so the EEDI is expected to stimulate innovation and development of all systems and components that influence the fuel efficiency of vessels[65].

Secondly the operational speed of a tanker can be reduced, also known as 'slow steaming. This is done to cut down fuel consumption and carbon emissions. Slow steaming is a well-known concept and has successfully helped ship owners in reducing the amount of fuel needed to run ships, which in turn has lead to significant decrease in carbon emissions[19].

Another high-potential solution is the use of alternative fuels. This can be LNG which can reduce carbon emissions, but only up to a limited amount. To decrease emissions even further, renewable fuels can be used. This are fuels which are produced in a sustainable manner. There are many candidates that could be used as renewable fuel on vessels such as renewable methanol, hydrogen, ammonia, ethanol or diesel, all having specific challenges and upsides[30].

CII

The use of these alternative fuels does pose one great challenge which how to measure the emission reduction achieved and how to implement this in the present regulation on carbon intensity reduction of vessels.

Presently the carbon intensity of vessels is expressed at the IMO using the 'Carbon Intenisty Indicator'(CII). The CII is an indicator that provides ship operators with the fraction of emissions that a vessel can emit compared to a benchmark. This is therefore not a one-time obligation but requires continuous improvement to comply with regulations. This continuously improving CII could follow the green line as can be seen in figure 1.2 if the CII requirements are identical to the IMO goals. This would result in a 70% reduction in 2050. This IMO goal is however only an expressed goal but has not been translated into strict regulation.

Presently are two main methods that can be used to measure the carbon intensity (i.e. carbon emissions “per ton mile”) of shipping that can be used when calculating the CII metric. The first is the Energy Efficiency Operational Indicator (EEOI) as proposed by the IMO. A second method is the Annual Efficiency Ratio (AER). The main difference lies in the calculation how much cargo the vessel transports. The EEOI is the ratio of a vessel's CO2 emissions per actual cargo transported divided by the distance sailed. The AER is the ratio of a vessel's CO2 emissions per vessel capacity divided by the distance that is sailed. I.e. the AER assumes that the vessel is always filled. Both methods express the CCI in the same units (g CO2/ton-mile).

The methods as described above both calculate emission using a carbon factor(CF). This factor only takes CO2 emissions in the tank-to-wake phase into account, neglecting well-to-tank emissions as well as other greenhouse gasses such as methane and N2O emissions. When comparing fossil fuels that emit the bulk of their emissions in the tank-to-wake (TTW) phase, this is a defensible approach. However when using alternative fuels, it is not always the case that the majority of emissions takes place during the TTW phase. For non-renewable ammonia for instance, almost all emissions take place during the well-to-tank(WTT) phase. Measuring the EEOI of a vessel operating on non-renewable ammonia using the EEOI or AER would therefore result in a theoretical carbon intensity reduction. However instead of actually reducing emissions, the emissions have merely been shifted to another phase in the production chain. The use of renewable fuels poses a similar problem, especially when considering different types of renewable fuels that all result in a different amount of emission reduction depending on the production process of the renewable fuel. Therefore to measure the actual carbon intensity reduction achieved by a vessel, emissions in both the WTT and TTW phase need to be taken into account. Measuring emissions in both these phases is known as a 'Life Cycle Analysis'[7]. Taking the entire well-to-wake system into account gives an complete overview of emissions and therefore gives an opportunity to compare the use of alternative fuels on an equal bases.

Cost of alternative fuels

While such renewable and alternative fuels can be used to reduce emission, the present use of especially renewable fuels is negligible due to expected high fuel costs over the lifetime of the ship compared to fossil fuels. These high fuel costs can reduce the return on investment significantly and deteriorate the competitive position of the shipping company[30]. However in the future the use of these renewable fuels can increase if regulation forces shipowners of tankers to reduce emissions. Indirect measures such as a carbon tax could also promote the use of renewable fuels because the cost of using fossil fuels would increase significantly. However when confronted with such regulation, it is important for shipowners to be able to select the most promising alternative fuel for their operations and vessel. These alternative fuels all have specific characteristics. Some fuels will be have relatively high capital cost, other fuels relatively high operational cost. Depending on the specifics of the trade, different fuels might then be the optimal solution. To find this optimal solution, good insight into the total costs ownership (TCO) of vessels using alternative fuels is needed. This can then help shipowners to be able to make substantiated design choices for future vessels.

Conclusion
In this section, the problem statement was explained. The IMO has expressed emission reduction goals which can be achieved by various measures such as increasing the efficiency of the vessel, slow steaming or using alternative fuels. However it is important when using alternative fuels that emissions are actually reduced and not shifted to a different phase such as fuel production. Furthermore good insight into financial impact of emission mitigating measures is required for shipowners to be able to make substantiated business choices.

1.1. State of Art & Research Gap

Evaluating the research that has been performed on alternative fuels it is clear that there is extensive research on the application and financial consequences of alternative fuels on vessels. Research can be found for the use of alternative fuels in various vessels such as cruiseships[71], container vessels [65], ferries[4], fishing vessels[25], dredgers[15] and tankers[62].

Within research performed on tankers two categories can be distinguished, one being research where the cargo is used as fuel and the other research where the tanker has a separate fuel tank. Research projects that focus on the use of the cargo as alternative fuel are performed by Methanex [48] and J. Tijdgat[66]. Methanol producer Methanex has been a forerunner in the application and research of this concept by using the transported methanol as fuel on board of their dual fuel tankers[48]. J. Tijdgat researched the use of renewable hydrogen carriers (RHC) as fuel on tankers[66]. These RHC are chemicals that can be used to transport hydrogen efficiently between locations by first reforming hydrogen to a chemical that is more easily transported.

Research on the application of alternative fuels on tankers with separate fuel tanks is performed by Baldi et al. [5]. MAN Energy solutions [62] also reviewed several fuels including methanol but did not review ammonia as potential fuel. Research on specifically ammonia for has been performed by N. de Vries[17].

Research on the life-cycle emission of fossil and renewable marine fuels is among others done by Bilgili [9], Hwang et al. [64] and Bengttson [7]. Research looking specifically at reducing emissions to meet IMO goals is done by Ampah et al.[3]

Research looking at the financial consequences of reducing life cycle emissions using alternative fuels is less extensive but performed for a roro-passenger ship in Croatia[54].

It can be concluded that extensive research is performed on the influence of alternative fuels on various aspect of shipping such as the design, life cycle emissions and cost of vessels. However there is a limited amount of research integrating these separate parts into one model while considering emission intensity reduction targets.

1.2. Research Objective

The research objective of this thesis is to develop a models that can help to gain better insight into the financial impact of using alternative fuels and speed reduction to comply with emission reduction regulation for a broad range of chemical tankers. This objective can be split into two sub-objectives:

- Developed a models that can evaluate the financial impact of using alternative fuels to comply with certain regulation.
- Developed a model that can evaluate the financial impact of using alternative fuels and speed reduction to comply with certain regulation.

By analysing both these objectives for a broad range of vessels and scenario's, trends could then be found. Some fuels have higher capital cost, other fuels higher operational cost which could lead to a different optimal fuel depending on the operations and size of the vessel. Analysing this could increase the insight into which fuels are most suited to help the chemical tanker fleet comply with specific decarbonization pathways and how speed reductions influence this. Design speed, capacity, operational range, and carbon taxes are varied to gain insight into a broad range of vessels and scenario's. Because the price of renewable fuels is strongly dependent on electricity prices, electricity price will be used as input variable and varied. Impact can be described as CAPEX, OPEX, Fuel cost, Carbon tax cost, Total cost of Ownership (TCO) and profit.

1.3. Research Questions

This section will give an overview the main research question and sub-questions.

Main research question
What is the financial impact of using alternative fuels and speed reductions on a chemical tanker to comply with decarbonization regulation, considering various carbon tax scenario's?

Sub-questions

1. What are the life cycle emissions of the selected fossil and renewable fuels?
2. What renewable fuel prices can be expected between 2025 and 2050 for renewable fuels depending on renewable electricity price scenario's and carbon tax scenario's ? And how do they compare to each other and to fossil fuels?
3. What is the financial impact of mixing in a minimal amount of renewable fuel with MGO on a chemical tanker to achieve a 70% emission intensity reduction during its entire lifetime? And can trends be found in which alternative fuel is optimal depending on multiple variables?
4. What is the financial impact of using renewable and fossil alternative fuels on a chemical tanker to comply with the IMO emission intensity goals? And can trends be found in which alternative fuel is optimal depending on multiple variables?
5. What is the financial impact of using speed reductions, renewable alternative fuel and fossil alternative fuels on a chemical tanker to comply with the IMO emission intensity goals? And can trends be found in which alternative fuel is optimal depending on multiple variables?

1.4. Research approach

In this section, the research approach is defined. This research approach will help to answer the research questions and to achieve the research goal. A general illustration of the research approach of this study can be seen as a flowchart in figure 1.3.

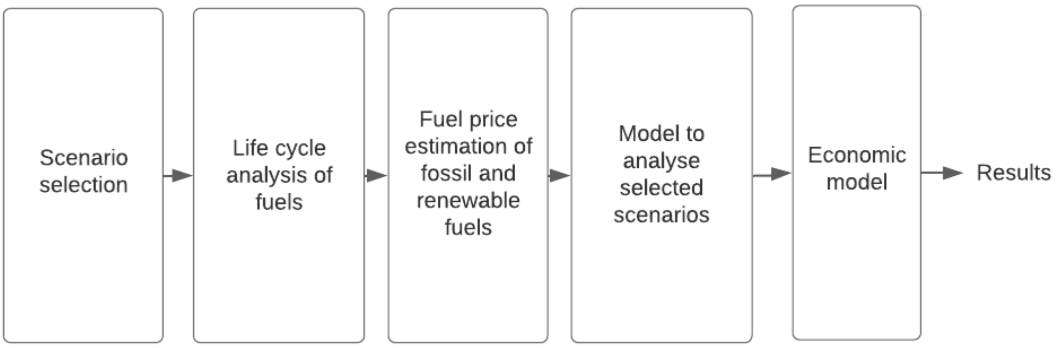


Figure 1.3: Overview of the research approach

First an overview of research scenarios that will be analysed in this study will be given in chapter 2.

A key input variable of the parametric and economic model are the life cycle emissions of the fuels. Therefore a life-cycle emission analysis is done of the selected fuels. An LCA is used to avoid shifting emission from the tank-to-wake phase to the well-to-tank phase. This is further explained and worked out in chapter 3.

Next a model is developed to be able to estimate the future prices of renewable fuels for various electricity price scenario's. This is done based on predicted capital and operational cost of fuel synthesis plants. This is the 'fuel price model' as is further elaborated on in chapter 4.

Next a 'model to analyse selected scenarios' will be developed in chapter 5. The first goal of this model is estimate the dimensions and characteristics of a chemical tankers based on deadweight and design speeds. This later enables the fast analysis of a broad range of vessels. The characteristics of this conventional vessel are then used to estimate the characteristics of a vessel with the same capacity but that can comply with the regulation as determined by the scenario through the use of alternative fuels.

An economic model is then developed to determine the vessels capital cost, operational cost, lifetime fuel cost, carbon tax cost and finally the total cost of ownership of the vessel. This model can be found in chapter 6.

These models then give all the tools to analyse the scenario's in chapter 7, 8 and 9.

2

Research scenarios

The research objective of this thesis is gain better insight into the financial impact of using alternative fuels and speed reduction on vessels to comply with possible emission regulation. Therefore multiple scenario's of regulation and technical solutions will be analysed in this study. The goal of this chapter is to select the scenarios.

Therefore all sub-parts from which scenarios can be created are discussed in this chapter in section 2.1, 2.4, 4.10 and 2.4. Next a combination of these sub-parts is selected to create the research scenarios, which will be done in section 2.5.

2.1. Decarbonization pathway

While the IMO has expressed carbon reduction goals for the future, no long term regulation on the emission intensity reduction of vessels has presently been implemented that can be used in this study as decarbonization objective. This study will therefore look at the following two hypothetical pathways:

- **Immediate 70% intensity reduction:** this pathways requires vessels to have reduced emission intensity by 70% in 2025 compared to a base case. This goal does not changing over the lifetime of the vessel. This is scenario is not an ambition expressed by the IMO, but could be the ambition of an operator.
- **Gradual implementation**: this pathway requires a continuous improvement of the carbon intensity over the years, with 2008 as reference point. A reduction of 40% should be achieved in 2030 and a emission intensity reduction of 70% in 2050. The annual emission reduction goals are assumed to follow a linear line between the set targets in 2008, 2030 and 2050.

2.2. Emission reduction strategies

In line with the research objective of this study, two emission reduction strategies are considered being "speed reductions" and "alternative fuels" as further explained below.

Speed reduction

The first strategy to reduce emission will be reducing the operational speed of the vessel.

Technical implementation of alternative and renewable fuels

Secondly alternative fuels can be implemented on a vessel. This can be done using several methods, these will be discussed below:

- **Mixing renewable diesel with MGO:** renewable diesel to can be added to the fossil diesel-oil on a vessel. The fraction of the renewable version can than be made as large as needed to achieve carbon reduction goals. This approach has limitations due to the inefficient production process of e-diesel, making it relatively expensive to produce and use[66]. This pathway is therefore not considered in this study.

- **Mixing of renewable alternative fuel with MGO:** To overcome the production problem of synthetic diesel it can be chosen to add a different renewable alternative fuel to a MGO powered engine. This renewable alternative fuel can be methanol, ammonia or another alternative renewable fuel. In that case the engine operates on a mixture of MGO and a renewable version of ammonia for example. Again depending on the required carbon reduction, the vessel can increase the fraction of renewable alternative fuel[63][4].

Figure 2.1: Implementation strategy using MGO and renewable alternative fuel

- **Complete switch to alternative fuel:** finally it can be chosen to completely switch to an alternative fuel such as LNG, ammonia of methanol. In past decade the use of LNG has increased significantly and is now commonly used on vessels. This strategy has also been used for the ferry Stella Germanica[4] which operates completely on methanol except some required pilot fuel. To be able to achieve its carbon goals, the vessel can then operates on a combination of the fossil and renewable version of the alternative fuel. If regulation become stricter over the years, the vessel can increase its share of renewable fuel to keep compliant.

Figure 2.2: Implementation strategy that makes a complete switch to an alternative fuel.

2.3. Carbon Emissions Tax

A emission trading system could be introduced in the future to reduce the emissions. Such a carbon tax aims to raise incentives for shipping companies to invest in technologies to enable cleaner shipping or switch to less emission intensive fuels. The height of the carbon tax will have large influence on its effect, therefore the following scenarios are considered:

- **Zero**
- **Low**
- **High**

2.4. Renewable prices

Shipowners generally aim to make a profit, and the cost of an emission militating solution such as alternative fuels will therefore have large influence on the use of that solution. How renewable fuel price will develop is uncertain and therefore two scenarios will be considered:

- **Low renewable fuel price**
- **High renewable fuel price**

2.5. Scenario generation

Combining the scenario's above, a large amount of combination of decarbonization pathways and strategies arises. For this study it is chosen to limit these combinations to three. The first combination is "immediate

70% intensity reduction" with a "Mixing of e-fuel with MGO" implementation strategy. Secondly the "Gradual implementation" decarbonization pathway is combined with the "complete switch to alternative fuel" technical implementation strategy. Thirdly the "Gradual implementation" decarbonization pathway is also combined with both a "complete switch to alternative fuel" strategy as wall as speed reductions. All these combinations are analysed for the different carbon tax and fuel price scenario's. An overview of these options can be found in table 2.1.

Decarbonization pathway	**Strategy**	**Carbon price**	**Power price**	**Scenario**
Immediate 70% intensity reduction in 2025	Addition of minimal amount e-fuels to MGO	None	high	1
			low	2
		Low	high	3
			low	4
		High	high	5
			low	6
Gradual Implementation	Complete switch to combination of fossil and renewable version of alternative fuel, to be able to yearly increase the use of e-fuel to keep compliant with increasingly stricter IMO goals.	None	high	7
			low	8
		Low	high	9
			low	10
		High	high	11
			low	12
Gradual implementation	Speed reduction + Complete switch to combination of fossil and renewable version of alternative fuel, to be able to yearly increase the use of e-fuel to keep compliant with increasingly stricter IMO goals	None	high	13
			low	14
		Low	high	15
			low	16
		high	high	17
			low	18

Table 2.1: An overview of all scenarios that will be analysed in this study

3

Life Cycle Analysis of fuels

To be able analyse the financial impact of using alternative fuels to comply with emission regulation, it is first important to determine the emissions connected to the fuels. This chapter will explain the reasons behind using a life cycle analysis to measure emissions. Therefore the concept of a LCA is explained in section 3.1 after which the analysis is done for the selected fuels in section 3.2.

3.1. Concept of a life cycle analysis

For the analysis of the environmental impact of fuel a life cycle assessment can be used. This process is also known as a Well-to-Wake analysis in the maritime industry and addresses the complete environmental impact of a fuel. Using LCA avoids shifting environmental impact from one phase in the life cycle to another phase which is essential to map overall environmental impact[7]. Within the life cycles of fuels, two phases can be distinguished as can be seen in figure 3.1. The first is the ”Well-to-Tank” (WTT) which is the phase from the acquisition of feedstocks such as oil to production/processing including finally transportation. The second phase is the ”Tank-to-Wake” (TTW) phase which spans from the tank of the vessel to final disposal. finally the term ”Well-to-wake” covers the complete process from cradle to grave.

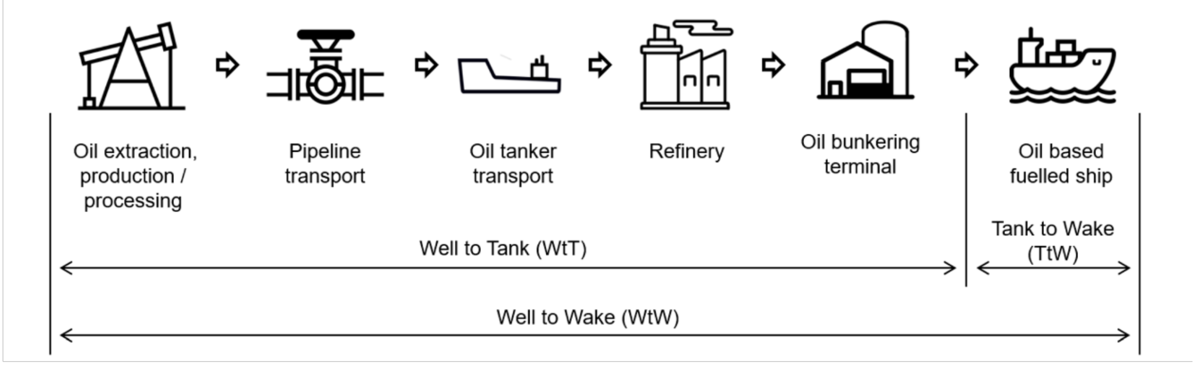


Figure 3.1: Illustration of the concept ’well-to-tank’ and ’tank-to-wake’ for fossil fuels[33]

The environmental impacts analysed in an LCA can be classified into five categories as shown below[64]:

- Global Warming Potential (GWP): An index for the radiative force of a given substance, accumulated over a time horizon, relative to the reference substance, being carbon dioxide (CO_2).
- Acidification Potential (AP): An index that measures the acidifying effect of substances.
- Photochemical Ozone Creation Potential (POCP): An index that gives an indication of the potential capacity of an organic compound to create ozone in the troposphere.
- Eutrophication Potential (EP): An index that measures the excessive biological activity of organisms due to over-nutrification.

- Particulate Matter (PM): An index to measure the secondary fine dust emitted into the atmosphere.

In this study only the Global Warming Potential will be reviewed, the other categories fall outside the scope of this study.

Global warming potential

The GWP of emissions is expressed as a "20-year GWP" or "100-year GWP" which are both indicators for the relative impact of a substance compared CO_2 over a respective timeframe, i.e. the 20-year GWP is based on the energy that is absorbed over 20 years by a substance. Because the impact is expressed relative to CO_2, this results in a theoretically higher GWP of gases with shorter lifetimes than CO_2 when considering the 20-year GWP.

This is particularly of relevance for methane. Since methane has a shorter atmospheric lifetime than CO_2, the 20-year GWP is higher than the 100-year GWP. The 20-year GWP of methane has been estimated to be 84, compared with the 100-year GWP of 28[69] as can be seen in table 3.1. This is relevant for this study because the impact of methane slip would have significant larger impact on the results when using a 20 year GWP[68]. In this study the 100 year GWP of substances will be used.

GWP	20 years	100 years
CO_2	1	1
NH4	84	28
N2O	264	265

Table 3.1: GWP of CO_2,NH4 and N2O.

3.2. Life cycle analysis of selected fuels

The life cycle emissions of the fossil variants of methanol, amonnia, LNG and MGO reviewed extensively in research[36][37][69]. Research into the life cycle emissions of renewable synthetic fuels produced from DAC and renewable fuels is is not as established. This study will therefore base the life cycle emissions of the renewable fuels on two factors. The first is the carbon-intensity of the wind power that is used for the production of e-fuels. The second factor is the carbon dioxide removed from the air by DAC as can be seen in equation 3.1. Values for the (negative) emissions of DAC are based on the values in chapter 4.

$$WTT_{\text{renewable fuel}} = \frac{\text{fuel energy}}{\eta_{\text{production}}} \cdot \text{carbon intensity}_{\text{electricity}} + \text{emissions}_{\text{DAC}} \tag{3.1}$$

The carbon intensity of wind energy is assumed to be 13 g CO_2-eq/kWh[43]. The used production efficiencies are 54.47%, 43.33% and 42.22% for respectively ammonia, methane and methanol. These are the efficiencies as determined in chapter 4 for the year 2020. It should be noted that other renewable energy sources such as hydro or solar have higher carbon intensities of respectively 28 and 73 g CO_2/kWh as can be seen in figure 3.2. Reviewing the influence of this difference in carbon intensity falls outside the scope of this project.

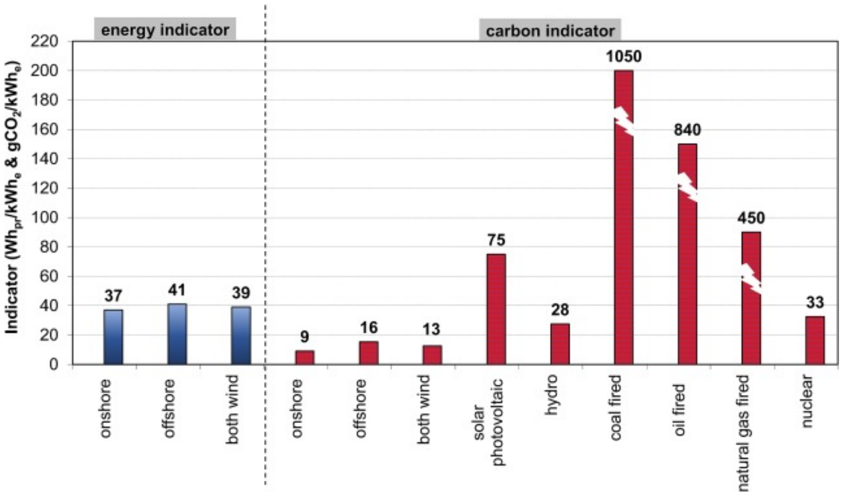


Figure 3.2: The carbon intensity of various power sources[43]

3.2.1. Life cycle analysis of ammonia

The life cycle analysis of renewable and fossil ammonia can be found in table 3.3. The WTT emissions of renewable ammonia is calculated using formula 3.1. The carbon footprint of grey ammonia depends on the feed stock and the efficiency of the ammonia plant. The difference in carbon footprint of ammonia plants is significant, plants that use coal as feed stock can have emission of up to 161 gr CO_2eq/MJ ammonia. However normally existing plants are more efficient, emitting approximately 161 gr CO_2/MJ ammonia[49]. Finally modern ammonia plants are the most efficient, being able to produce with emissions as low as 86 gr CO_2eq/MJ ammonia[44]. This study will use a value of 96.5 gr CO_2eq/MJ[69].

Harmful emissions of Ammonia	**[g/g-fuel]**	**[g CO_2-eq/MJ]**	**Source**
WTT			
WTT Fossil ammonia		96.50	[44]
WTT Synthetic ammonia		6.62	Calculations
TTP			
CO_2	0	0	[14]
CH4	0	0	[14]
N2O	0.000080	1.13	[14]
Sub-total		1.13	
WTP Fossil Ammonia		97.6	
WTP Synthetic Ammonia		7.76	

Table 3.2: The life cycle emissions for renewable and fossil ammonia. Sources can be found in the table. The WTT of fossil ammonia is the average value of the higher and lower limit of 86-107 kg CO_2 eq eq/GJ[44]. The N2O emission of ammonia engines is unknown and should be verified by an engine manufacturer, for now it is assumed that NH3 (dual fuel) performs similar as HFO in g/kWh

3.2.2. Life cycle analysis of methanol

The life cycle analysis of renewable and fossil methanol can be found in table 3.3. The WTT emissions of renewable methanol is calculated using formula 3.1. The life-cycle emissions of fossil methanol are built up from extraction of methane, transport and processing. The amount of emissions affiliated with the extraction of natural gas strongly depend on the location, ranging from 2 gr CO_2eq/MJ in Norway to 8 gr CO_2eq/MJ in Russia. However overall the total well-to-tank (WTT) GHG emissions from methanol production made from natural gas is strongly dominated by the emissions from the combustion from natural gas during methanol production at the plant. Transport emissions are almost neglectable. This results in 20.38 gr CO_2eq/MJ for methanol when produced from natural gas[69].

Harmful emissions of Methanol	**[g/g-fuel]**	**[g CO_2-eq/MJ]**	**Source:**
WTT			
WTT Fossil Methanol		20.38	[69]
WTT Synthetic Methanol		-60.44	Calculations

TTP			
CO_2	1.37	69.00	[69]
CH4	0	0	[69]
N2O	0	0	[69]
Sub-total		69.00	

WTP Fossil		89.38	
WTP Synthetic wind		8.55	

Table 3.3: The life cycle emissions for renewable and fossil methanol. Sources can be found in the table.

3.2.3. Life cycle analysis of methane

Harmful emissions of LNG	**[g/g-fuel]**	**[g CO_2-eq/MJ]**	**Source**
WTT			
WTT Fossil LNG		19.46	[69]
WTT Synthetic LNG		-47.80	Calculations

TTP			
CO_2	2.75	56.12	[36]
CH4	0.02	11.42	[36]
N2O	0.000110	0.59	[36]
Sub-total	-	68.14	

WTP Fossil LNG		87.61	
WTP Synthetic LNG		20.33	

Table 3.4: The life cycle emissions for renewable and fossil LNG. Sources can be found in the table.

3.2.4. Life cycle analysis of MGO

3.3. Comparison of results

An overview of results of the LCA analyses can be seen in figure 3.3. It can be seen that e-LNG still has significant GHG emissions due to methane slip but still results in approximately 77% reduction compared to fossil LNG. for e-ammonia and e-methanol significant lower life cycle emission were found, resulting in respectively a 92% and 90% emission reduction. Furthermore it was found that while e-ammonia has the lowest life-cycle emission, the fossil version has the highest due to the production process.

Harmfull emission of MGO 0.1% S	**[g/g-fuel]**	**[g CO_2-eq/MJ]**	**Source:**
WTT			
WTT Fossil MGO 0.1% S		12.92	x

TTP				
CO_2	3.16	74.00	x	[h!]
CH4	0.000019	0.013	x	
N2O	0.000149	0.92	x	
Sub-total		74.94		

WTP Fossil MGO 0.1% S		87.86	

Table 3.5: The life cycle emissions for renewable and fossil methanol. Sources can be found in the table.

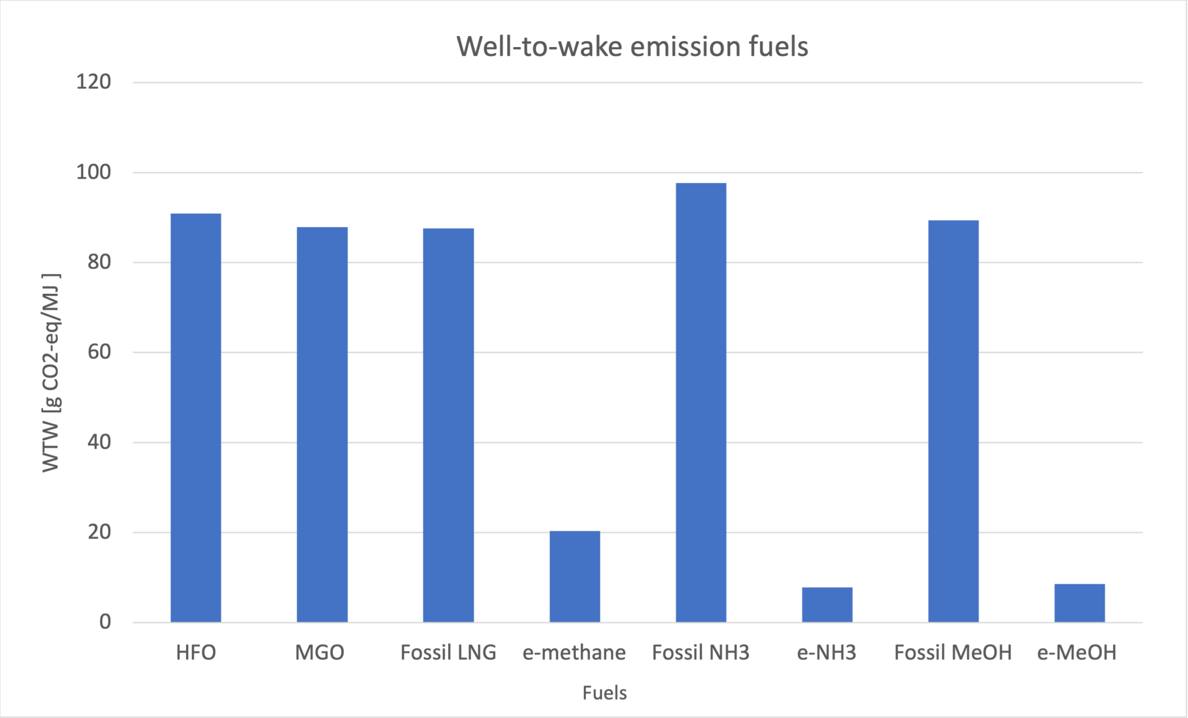


Figure 3.3: The well to wake emissions of fuels

3.4. Conclusion

The goal of this chapter was to map the life cycle emission of various fuels. For the LCA the greenhouse gasses CO_2, N20 and CH4 were considered and their impact as GHG has been measured as the 100 year CO_2eq. It was found that e-LNG still has significant GHG emissions due to methane slip but still results in approximately 77% reduction compared to fossil LNG. For e-ammonia and e-methanol significant lower life cycle emission were found, resulting in respectively a 92% and 90% emission reduction.

4

Fuel price estimation of fossil and renewable fuels

The goals of this chapter is to give a overview of the production and availability of ammonia, methanol and LNG. This is done by reviewing different types and availability of ammonia, methanol and LNG in respectively section 4.1 and 4.6.

Next in section 4.4 an analysis will be made of energy demand and capital costs of the feedstocks of synthetic fuels. The synthetic production of green ammonia, methanol and LNG will be reviewed in respectively section 4.5,4.6 and 4.7. Finally an overview of expected fuel costs will be given in section 4.8 for renewable fuels and in section 4.9 for fossil fuels.

4.1. Types and availability of ammonia

Ammonia has a long history of large scale production, and is a globally traded commodity. Depending on the energy source for the production om ammonia, different types of ammonia can be distinguished such as grey, blue and green ammonia. While these types of ammonia have different carbon dioxide footprints, the physical product 'ammonia' is identical. Below the different types of ammonia of ammonia will be reviewed[44]:

- **Grey ammonia** is normally produced from fossil energy sources, usually natural gas. The ammonia production plant turns these fossil sources into gaseous hydrogen, a process known as steam reforming. Next this hydrogen is used in combination with nitrogen to make ammonia using the Haber-Bosch process[44].
- **Blue ammonia** has a similar production process as grey ammonia, having one difference which is that the carbon emissions from the ammonia plant are captured and stored at a permanent location. This process is known as carbon capture and storage (CCS)[44], hence significantly reducing the carbon footprint of the ammonia[44].
- **Green ammonia** is produced completely from renewable electricity, air and water. This type is therefore also known as renewable or sustainable ammonia. It is assumed that the carbon footprint of ammonia from this production method is close to zero. For it to be completely zero-emissions, the entire industry including transport will need to become sustainable. At the moment not all life cycle emission can be reduced to zero, the reduction in carbon emissions for green ammonia is therefore estimated at more than 90% for wind power-based ammonia. For solar based ammonia the emission reduction is estimated at 75%[44].

Ammonia availability

The worldwide production of ammonia has been increasing over the last decades steadily. Production has a high correlation with the growth of the world population because 85% of all ammonia is used for the production of fertilisers. At the moment the total world production of ammonia is approximately 180 million tons

[44] while the worldwide production capacity is 243 million tons. Therefore only 75% of the present production capacity is actually used to produce ammonia. The most plausible reasons for the large gap is the high age of many ammonia plants. However, even corrected for age, a higher production output of 90% can be expected[44], leaving the possibility to increase production by 40 million tons.

The industrial production of green ammonia is presently almost non-existant, however the transitioning towards an sustainable ammonia production industry is accelerating. In 2020 multiple large-scale projects for the production of green ammonia were announced which could lead to the availability of millions of tons of low-carbon ammonia this decade[11]. The world's largest ammonia manufacturer, CF Industries has set a target to achieve net-zero carbon emissions by 2050. Therefore they will first build a 20,000 ton green ammonia production facility in the U.S.A. Furthermore Fertiberia and Iberdrola announced their intention to expand their existing green ammonia plans, from a 20 MW pilot plant that will be operational next year, to a full 800 MW of electrolytic hydrogen production by 2027[11].

The total marine fuel consumption is currently approximately 250 million tons. To put the present production capacity of ammonia into perspective, it would require approximately 150 million tons of ammonia a year to replace 30% of the current marine fuel consumption according to white paper Ammonfuel[44]. Hence additional production capacity is most likely needed if the application of ammonia as a marine fuel becomes significant.

Since more green ammonia production capacity is being build, the production of green ammonia could gradually replace fossil based ammonia. However the fossil based variant will remain important for the coming decades. For that reason, future vessels might have to use combination of green and fossil while the full transition is still ongoing. To give more insight into the availability of both green and grey ammonia, DNV GL has located all ammonia bunker locations worldwide. This data is published in their 'Alternative Fuels Insight' online tool. Figure 4.1 shows the ammonia available bunker locations from this tool[27].

Figure 4.1: Wordwide bunker locations for ammonia according to DNV GL [27]

4.2. Types and availability of methanol

Methanol is generally produced from coal, natural gas or biomass. The following types of methanol can be distinguished depending on the source of the energy[41]:

- **Grey Methanol;** Worldwide most methanol is produced by the synthesis of natural gas. Steam reforming and partial oxidation are the chemical processes that are mainly used to produce syngas from which methanol can be produced.

- **Blue methanol** has a similar production process as grey methanol, having one difference which is that the carbon emissions from the methanol plant are captured and stored at a permanent location. This process is known as carbon capture and storage (CCS)[44], and can reduce the carbon footprint of the fuel[44] partially.

- **Green methanol from carbon neutral biomass;** Presently methanol is made mainly from fossil resources, however in the future a (gradual) transition to methanol produced in a sustainable manner is required to reduce emissions significantly. Methanol production from biomass such as wood or food residues is one way of producing sustainable methanol. Wood residues are a biomass source because it can be converted into black liquor which can be gasified to syngas which is needed for the production of methanol. In the future such processes could become part of large wood processors that have excess biomass. In the end such a sustainable way of producing methanol can make methanol a clean fuel with low well-to-wake (WTW) emissions[42].

- **Green synthetic methanol;** Another sustainable method for the synthesis of methanol is production from green hydrogen (from electrolysis with sustainable electricity). This method uses a reverse water gas shift reaction (RWGS) between hydrogen and captured CO_2 to produce a mixture of CO and H2O. Next the CO is separated, and mixed with H2 to form (green) syngas from which methanol can be produced[41].

Methanol availability

The production of methanol is distributed over approximately 90 methanol plants in Asia, North and South America, Europe, Africa and the Middle East and totalled to about 95 million metric tons in 2018[2]. Production capacity in not used completely since these methanol plants have a combined production capacity of about 110 million metric tons. This production is mainly driven by energy applications for methanol since it is primarily used as a chemical feedstock or as a transportation fuel[42]. The key importers of methanol are the US and China, both importing around 5 million metric tons of methanol annually[42].

Production of green methanol from biomass is still limited. A new methanol plant from BioMCN in the Netherlands is the first large scale bio-methanol plant and produces 200,000 tonnes/year by producing bio-methanol from biogas sourced from waste digestion plants. Production of green methanol from green hydrogen is also still very limited and no large-scale plant exist yet but several pilot-plants are being build. North-C-Methanol is one of these demonstrator projects that is presently being build. It consists of an electrolyser plant with a power of 63 MW, splitting water in green hydrogen and oxygen, using renewable energy from off-shore wind. Oxygen will be used locally in the steel industry. Green hydrogen will be combined with captured CO_2, originating from industrial point sources, in a catalytic methanol synthesis plant with a production capacity of 45.000 ton methanol per year[12]. Because CO_2 is sourced from industrial sources for this plant, the process is still not a closed cycle but could become so if CO_2 is sourced from the air.

The total marine fuel consumption is currently approximately 250 million tons[44]. To put the present production capacity of methanol into perspective, it would require approximately 160 million tons of methanol a year to replace 30% of the current marine fuel consumption. This estimation is based on the LHV of methanol and MGO and only gives a rough estimation. Considering the present methanol production of 96 million tons it shows that a significant increase in production capacity would be needed if the application of methanol as a marine fuel increases to substantial levels.

DNV GL located all methanol bunker locations worldwide and published them in their 'Alternative Fuels Insight' online tool. Figure 4.2 shows the methanol available bunker locations from this tool[27]. It can be noted that worldwide supply is existing, however less developed area's such as West-Africa do not have available bunker locations.

4.3. Types and availability of methane

Methane is a product that is generally available in a non-pure form as natural gas or liquefied natural gas(LNG) but other types can also be distinguished:

- **Grey methane:** Presently almost all methane worldwide comes from natural gas.

Figure 4.2: Wordwide bunker locations for methanol according to DNV GL [27]

- **Green methane** can be sourced from bio-mass or produced synthetically. Synthetic methane is also known e-methane due to the fact that the production process of this variant is dependant on electrcity.

4.4. Feedstocks of synthetic fuels

The previous sections have given a general overview of available types of ammonia, methanol and methane. It was found that renewable fuels can be produced from bio-mass or from electricity using synthesis. This study will limit its scope to synthetic renewable fuels. The most important elements for the production of synthetic fuels are renewable energy, hydrogen, nitrogen and carbon dioxide. Therefore this section will further review these elements before the synthetic production of fuels itself is further analysed in section 4.5 and on.

Therefore the cost of renewable energy will first be reviewed. Next the production processes of hydrogen, nitrogen and carbon dioxide are reviewed.

4.4.1. Renewable energy

The cost of renewable energy in this study has been based on data from International Renewable Energy Agency and can be seen by year in table 4.1[38][40].

Electricity price	**2020**	**2030**	**2050**
Scenario 1: High [USD/kWh]	0.056	0.050	0.030
Scenario 1: high average [USD/GJ]	15.556	13.889	8.333
Scenario 2: Low best [USD/kWh]	0.056	0.04	0.02
Scenario 2: Low best [USD/GJ]	15.556	11.111	5.556

Table 4.1: Energy prices from IRENA[39].

4.4.2. Electrolysis

There are multiple ways to produce hydrogen from renewable power such electrolysis, thermolysis, and thermochemical cycles. The most used and mature process at the moment is electrolysis, therefore this method will be reviewed in this study. During electrolysis, water is separated into hydrogen and oxygen by a current between two electrodes as can be seen in formula 4.1[13].

$$2 \cdot H_2O + \text{electricity} = 2 \cdot H_2 + O_2 \tag{4.1}$$

Electrolysers can be categorised into low- and high temperature electrolysers. For low-temperature electrolysis there are two main technologies which are Proton Exchange Membrane (PEM) and Alkaline Electrolysis Cells (AEC). For high temperature electrolysis, Solid oxide electrolysis cell (SOEC) is the main technology[20]. An overview of these technologies can be seen in table 4.3. At the moment only AEC electrolysers are commercially available, therefore this technology will be used in this study.

Table 4.2: Overview of AEC, PEM and SOEC electrolysters[20]

Technology	**Low temperature**						**High temperature**		
	AEC			**PEM**			**SOEC**		
Year	2017	2030	2050	2017	2030	2050	2017	2030	2050
TRL(Assumption)	8-9	9	9	7-8	9	9	5-7	9	9
Maturity	Commerical			Commercial but small scale			Demon-stration	Commercial	

Table 4.3: The technology readiness level of the main electrolyser technologies[20].

The efficiency of an alkaline electrolyser is estimated at 66% in 2020,68% in 2030 en 75% in 2050[38] as can be seen in table 4.4. The capital costs are estimated at 696 USD per ton hydrogen in 2020 and are set to decline to 122 USD per ton hydrogen in 2050. The CAPEX of the electrolyser[38], OPEX[13], replacement cost[13], plant lifetime[13], capacity factor[13] and stack lifetime in 2020[13], 2030[13] and 2050 [16] supporting these numbers can be found in table 4.4.

Energy demand electrolyser	**2020**	**2030**	**2050**
Electrolysis efficiency [%] (LHV)	66	68	75
Electrolysis [GJ/ton H2]	181.82	176.47	160.00
CAPEX electrolyser	**2020**	**2030**	**2050**
CAPEX Electrolyser [$/kWel]	840.00	626.67	200.00
OPEX [%]	3.50	3.50	3.50
Stack lifetime [h]	75000	95000	125000
Stack replacement cost [% of CAPEX]	50.00%	50.00%	50.00%
Plant lifetime [years]	30.00	30.00	30.00
Capacity factor [%]	80.00	80.00	80.00
Total CAPEX [USD/ton H2]	696.50	461.21	122.23

Table 4.4: The efficiency of electrolysis in 2020, 2030 and 2050 are the average of the range estimated by the IEA[34] for these years. CAPEX based on IRENA[38]. OPEX, Replacement cost, Plant lifetime and capacity factor are based on Selma et al.[13]. Stack lifetime in 2020 and 2030 based on [13]. Stack lifetime in 2050 based on [16].

4.4.3. Direct Air Capture of CO_2

For the production of synthetic hydrocarbons, carbon dioxide is needed as a feedstock. Carbon dioxide can either be captured from point sources (PC) or alternatively it can be captured from ambient air by direct air capture (DAC). While carbon capture from point sources might reduce overall emissions it is not carbon neutral. Therefore only carbon capture by means of DAC is considered in this study[20].

DAC systems have the main advantage that they do not depend on CO_2 point sources. Therefore they can be directly integrated into an synthetic fuel production plants, i.e. saving CO_2 transportation costs. Furthermore this enables fuel production at locations with high power availability but without carbon dioxide sources. A downside of DAC system are the high energy demand and costs compared to capture from point sources. This is a result of the relative low CO_2 concentration of 0.04% in ambient air. In contrast, the carbon dioxide level in flue gasses of gas and coal power plants are respectively 3-10% and 12-15%[20].

At the moment DAC is technically feasible and several demonstration plants have been build. Some have been developed at commercial scale and the technology can be considered near to commercial available. The energy demand of DAC systems used in this study is 1535 kWh/ton$_{\mathrm{CO2}}$ in 2020, 1458 kWh/ton$_{\mathrm{CO2}}$ in 2030 and 1316 kWh/ton$_{\mathrm{CO2}}$ in 2050[23]. The capital costs of DAC are calculated using variables as found in table 4.5, this gives an estimated CAPEX of 33.8 USD/ton CO_2 in 2020, 9.16 USD/tonCO_2 in 2030 and 7.76 USD/tonCO_2 in 2050[23].

Energy demand	**2020**	**2030**	**2050**
DAC GJ/ton CO_2	5.53	5.25	4.74

CAPEX			
CAPEX [USD/(t CO_2 an.)]	815.00	265.00	222.00
Lifetime [years]	25	30	30
CAPEX [USD/ton]	32.6	8.83	7.4

OPEX			
OPEX [% of capex p.a.]	3.70	3.70	3.70

Total CAPEX + OPEX DAC [$/ton CO_2]	33.81	9.16	7.67

Table 4.5: Energy demand[23] and capital cost[23] of DAC. The CAPEX is first shown as capital cost per ton production capacity. Dividing this by the lifespan of the system gives the cost per ton CO_2.

4.4.4. Air separation of nitrogen

To separate nitrogen from air, an air separation unit (ASU) can be used. The power requirements for the ASU unit are estimated at 200 MJ/ton N_2[31]. The capital cost are estimated at 2.78 USD per ton nitrogen, based on variables as can be seen in table 4.6.

Energy demand ASU	**2020**	**2030**	**2050**
N_2 separation (ASU) [GJ/ton N_2]	0.2	0.2	0.2
CAPEX ASU	**2020**	**2030**	**2050**
CAPEX [USD/kW]	13182	13182	13182
OPEX [% of capex p.a.]			
Lifetime [years]	30	303	30
CAPEX [USD/ton N_2]	2.78	2.78	2.78

Table 4.6: The power requirements[31] and variables used to calculate capital costs[50] of an air separation unit.

4.5. Synthesis of Ammonia

4.5.1. Production process & energy demand

To produce ammonia from hydrogen and nitrogen, the Haber and Bosch process is used and the chemical equation of this process is shown in equation 4.2. This production process is performed at an operating pressure between 100 - 250 bar and a temperature between 400 and 500 degrees Celsius. Furthermore iron oxide based catalyst is present in this process to support the chemical reaction[1].

$$N_2 + 3H_2 = 2NH_3 \ (+Heat) \tag{4.2}$$

For the production of 1 ton of ammonia using the Haber-Bosch Process, 178 kg of hydrogen is needed. For the production of the required green hydrogen, electrolysis is used which is estimated at an efficiency of 58% in 2017 and is expected to increase as is explained in further detail in section 4.4.2

For the production of the required nitrogen, an air separation unit (ASU) can be used to separate the nitrogen from the air. The ASU requires 200 MJ for the production of 1 ton N_2
citeThesis$_Nielsandusing822kg$$N_2$ for 1 ton of ammonia, this requires 160 MJ/ton NH_3[17]. It is assumed that the energy consumption of this process remains constant over the years.

For the synthesis ammonia, the nitrogen and hydrogen are compressed and inserted into the Haber-Bosch reactor. The synthesis of ammonia with the Haber-Bosch process requires an additional 1600 MJ/ton NH3[31]. An overview of the energy consumption of ammonia production can be seen in table 4.7.

Ammonia	**Mass needed [ton]**	**Energy needed 2020**	**Energy needed 2030**	**Energy needed 2050**
Electrolysis [GJ/ton NH3]	0.18	32.36	31.41	28.48
Separation N_2 [GJ/ton NH3]	0.82	0.16	0.16	0.16
Synthesis [GJ/ton NH3]		1.60	1.60	1.60
Liquifaction [GJ/ton NH3]		0.01	0.01	0.01
Total [GJ/ton NH3]		34.14	33.19	30.25
Efficiency (LHV) [%]		54.48	56.05	61.48

Table 4.7: The energy consumption of ammonia production. Electrolysis based on [38]. ASU, synthesis and liquifaction based on [31].

Capital costs

The capital cost of ammonia are based on the capital cost of ASU and electrolysis as discussed in respectively section 4.4.4 and 4.4.2. For the synthesis of ammonia using an Haber Bosch reactor, capital costs of 122.09 USD per ton ammonia are assumed[66]. An overview of capital cost for ammonia can be found in table 4.8

Ammonia CAPEX	**Mass needed [ton]**	**2020**	**2030**	**2050**
CAPEX electrolysis [USD/ton NH3]	0.18	123.98	82.10	21.76
CAPEX ASU [USD/ton NH3]	0.82	2.29	2.29	2.29
CAPEX synthesis + liquifaction [USD/ton NH3]		122.09	122.09	122.09
Total CAPEX [USD/ton NH3]		248.35	206.47	146.13

Table 4.8: The capital expenses of ammonia.

4.6. Synthesis of methanol

4.6.1. Production process and energy demand

Green methanol can be produced using a reverse water gas shift reaction (RWGS). In this reaction green hydrogen and CO_2 are reformed into carbon mono oxide and water. This can be seen in equation 4.3. Next, the carbon dioxide is separated, and CO and additional CO_2 are mixed with H2 to form (green) syngas. Finally the syngas is used to form methanol in reactor as is shown by equation 4.4. This reaction is exothermic and high pressures are needed to enable the reaction.

$$CO_2 + H_2(+Heat) = CO + H_2O \tag{4.3}$$

$$CO + 2H_2 = CH_3OH(+Heat) \tag{4.4}$$

In this study electrolysis is used for the production of the required green hydrogen. The efficiency of this process is estimated at 58% in 2017 and is expected to increase as has been discussed in the section 4.4.2. For the production of the required carbon dioxide, DAC is used as further explained in section 4.4.3. Finally it is assumed that the synthesis of methanol requires 4.8 GJ/ton. These values are summarised in table 4.9.

Methanol	**Mass needed [ton]**	**Energy needed 2020**	**Energy needed 2030**	**Energy needed 2050**
Electrolysis [GJ/ ton MeOH]	0.19	34.36	33.35	30.24
DAC [GJ/ ton MeOH]	1.44	7.97	7.57	6.83
Synthesis [GJ/ ton MeOH]		4.80	4.80	4.80
Total [GJ/ton]		47.13	45.72	41.87
Efficiency (LHV) [%]		42.22	43.52	47.53

Table 4.9: The energy demand electrolysis[34], DAC[23] and synthesis[66] for methanol production.

Capital cost of methanol production

The capital cost of methanol are based on the capital cost of DAC and electrolysis as discussed in respectively section 4.4.3 and 4.4.2. For the synthesis of methanol using an RWGS, capital costs of 143.02 USD per ton methanol are assumed[66]. An overview of capital cost for methanol can be found in table 4.10

Methanol total cost	**Mass needed [ton]**	**2020**	**2030**	**2050**
CAPEX electrolysis [USD/ton MeOH]	0.19	131.64	87.17	23.10
CAPEX DAC [USD/ton MeOH]	1.44	48.75	13.21	11.07
CAPEX synthesis + liquifaction [USD/ton MeOH]		143.02	143.02	143.02
Total capex [USD/ton MeOH]		323.41	243.40	177.19

Table 4.10: The capital costs of electrolysis[38], DAC[23] and synthesis[66] of methanol.

4.7. Synthesis of methane

4.7.1. Production process & energy demand

Synthetic natural gas (SNG) can be produced synthetically by methanation, a process is performed trough the Sabatier reaction which is shown in equation 4.5 In this process CO_2 and H_2 react to form water and methane. Next to methanisation, synthetic methane can be produced through the reverse reaction of steam methane reforming. In this process carbon monoxide and hydrogen react to form methane as can be seen in equation 4.6. To produce the required carbon monoxide, endothermic reversed water gas shifting (RWGS) can be used as shown in equation 4.7. The most widely used process is the combination of an endothermic reversed water gas shift (RWGS) reaction and an exothermic CO methanation[20].

$$CO_2 + 4H_2O = CH_4 + 2H_2O \text{ (+Heat)} \tag{4.5}$$

$$CO + 3H_2 = CH_4 + H_2O \text{ (+Heat)} \tag{4.6}$$

$$CO_2 + H_2 + \text{Heat} = CO + H_2O \tag{4.7}$$

In this study electrolysis is used for the production of the required green hydrogen. The efficiency of this process is estimated at 58% in 2017 and is expected to increase as has been discussed in the section 4.4.2. For the production of the required carbon dioxide, DAC is used as further explained in section 4.4.3. The energy demand of the methanation is set at 1,2 GJ/ton methane[31]. Finally the liquefaction process has an energy demand of 5GJ/kg[17]. These values are summarised in table 4.11.

Methane	**Mass needed [ton]**	**Energy needed 2020**	**Energy needed 2030**	**Energy needed 2050**
Electrolysis [GJ/ton CH4]	0.50	91.45	88.76	80.48
DAC [GJ/ton CH4]	2.74	15.14	14.38	12.98
Synthesis [GJ/ton CH4]		1.20	1.20	1.20
Liquifaction [GJ/ton CH4]		5.00	5.00	5.00
Total [GJ/ton CH4]		112.80	109.35	99.66
Efficiency (LHV) [%]		43.44	44.81	49.17

Table 4.11: The energy consumption of electrolysis[34], DAC[23], synthesis[31] and liquefaction[17] for the production of methane.

Capital costs of methane

The capital cost of methane are based on the capital cost of DAC and electrolysis as discussed in respectively section 4.4.3 and 4.4.2. For the synthesis of methane using the methanisation, capital costs of 330,23 USD per ton methane are assumed[66]. An overview of capital cost for methane can be found in table 4.12.

Methane CAPEX	**Mass needed [ton]**	**2020**	**2030**	**2050**
CAPEX Electrolysis [USD/ ton CH4]	0.50	350.34	231.99	61.48
CAPEX DAC [USD/ ton CH4]	2.74	92.63	25.10	21.03
CAPEX Synthesis [USD/ ton CH4]		330.23	330.23	330.23
Total CAPEX [USD/ ton CH4]		773.20	587.32	412.74

Table 4.12: The capital cost of electrolysis[38], DAC[23] and synthesis/liquefaction[66] for methane production

4.8. Price of synthetic fuels

The total production cost (TC) of the synthetic fuels in can be calculated by formula 4.8.

$$\text{Total costs (TC)} = \text{CAPEX} + \text{energy demand} \cdot \text{energy prices} \tag{4.8}$$

The results can be found in table 4.13 for scenario 1 (average wind) and scenario 2 (best wind). These results can also be found in figure 4.3 and 4.4

Validation

The calculated fuel prices were compared with literature to validate the calculations. For e-ammonia it was found that prices of $ 465 to $ 1000 are expected for 2025 to 2030, which is a relatively wide range, but the calculated price fall within this estimate[44]. For 2040 to 2050, expected prices of $ 319 to $ 523 were found, which are again comparable prices to the calculated prices[44]. The cost of e-methanol is expected to decrease to levels between USD 250-630/t by 2050 according to IRENA, which is a wide range compared to the range in this study but does correspond with the found prices. For e-methane, prices of $ 1392 to $3102 were found in literature for 2030[20]. For 2050 price estimates were found from $1202 to $2186 for e-methane which is higher than the own estimate.

4.9. Price of fossil fuels

The price of fossil fuels in this study is based on prices in October 2020 and are kept steady over the years. An overview can be found in table 4.14

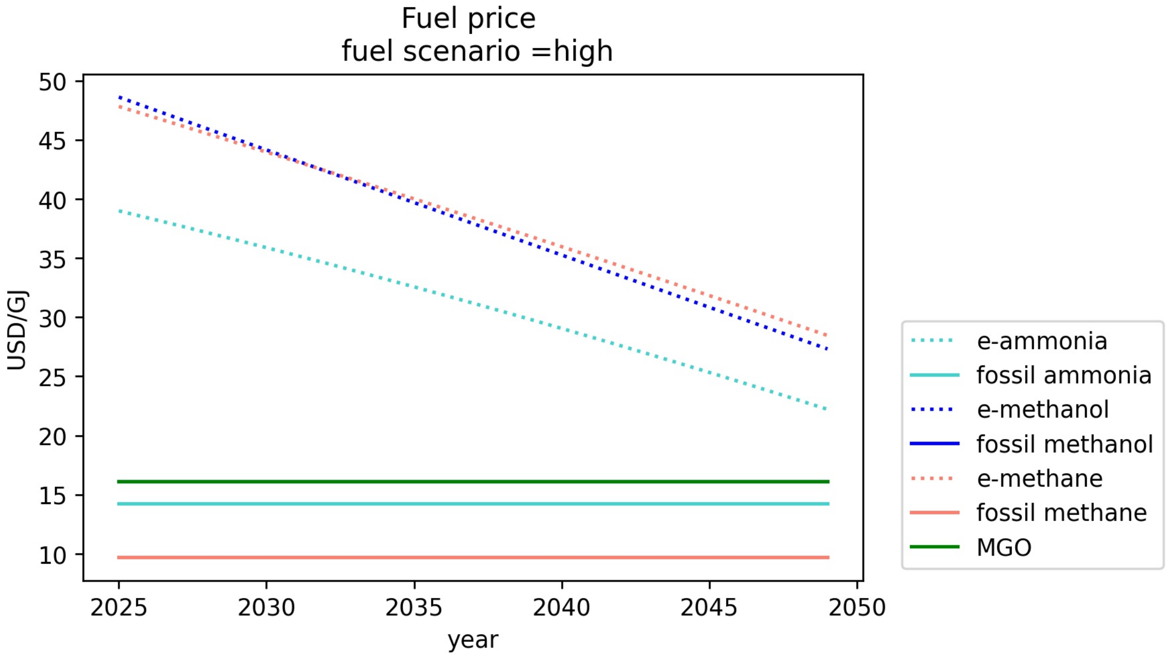


Figure 4.3: The fuel prices as calculated for the 'high' electricity price scenario.

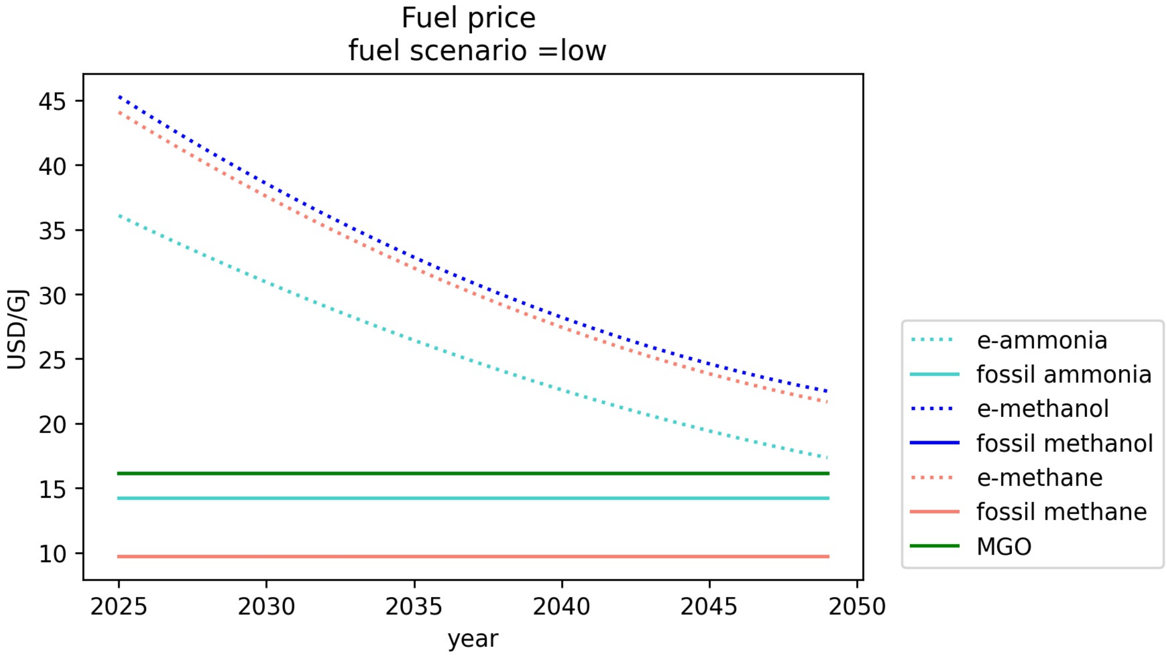


Figure 4.4: The fuel prices as calculated for the 'low' electricity price scenario.

4.10. Carbon Emissions Tax

A carbon emission trading system could be introduced in the future to reduce the carbon emissions and can have a large impact on the costs of shipping. This study will therefore also look at the consequences of carbon taxes on the TCO of vessels using alternative fuels.

A carbon tax can include only carbon dioxide emissions or can also include other greenhouse gasses. These include methane (CH_4) and nitrous oxide (N_2O) which expressed as (CO_2) equivalent emission. Furthermore

Fuel prices for 'high' fuel price scenario	2020	2030	2050
e-Ammonia [USD/ton NH3]	779.39	667.39	398.25
e-Methanol [USD/ton MeOH]	1056.58	878.43	526.12
e-Methane [USD/ton]	2527.80	2153.93	1352.70
e-Ammonia [USD/GJ NH3]	41.90	35.88	21.41
e-Methanol [USD/GJ]	53.09	44.14	26.44
e-Methane [USD/GJ]	51.59	43.96	27.61

Fuel prices for 'low' fuel price scenario	2020	2030	2050
e-Ammonia [USD/ton NH3]	779.39	575.21	314.21
e-Methanol [USD/ton MeOH]	1056.58	767.09	439.04
e-Methane [USD/ton]	2527.80	1840.61	1039.38
e-Ammonia [USD/GJ NH3]	41.90	30.93	16.89
e-Methanol [USD/GJ]	53.09	38.54	22.06
e-Methane [USD/GJ]	51.58	37.56	21.21

Table 4.13: Development of fuel costs. Prices of MGO, LNG and Methanol based on Baldi at al.[5]. Price of ammonia based on the relative cost of ammonia compared to methanol

Fossil fuel	Price in 2020	Price in 2030	Price in 2050
MGO [USD/ton]	689.6	689.6	689.6
LNG [USD/ton]	474.8	474.8	474.8
MeOH [USD/ton]	321.4	321.4	321.4
NH3 [USD/ton]	265	265	265

Table 4.14: Prices of fossil fuels as used in this study. Prices of MGO, LNG and methanol based on Baldi at al.[5]. Price of ammonia based on the relative price of ammonia compared to methanol as found by Moya et al.[10] and the methanol price as used in this study.

it is up to the authorities to include or exclude the greenhouse gas emissions that result from the combustion of renewable carbon bases fuels such as e-methanol. In this study all greenhouse gas emissions (CO_2,CH4 and N2O) including those of renewable fuels need to be paid for.

The Intergovernmental Panel on Climate Change researched how high a carbon tax should be to be able to meet the requirements of the Paris Accord. They found that the majority of scenarios with a greater than 66% chance of limiting temperature change to less than 2 °C are those that reach between 430 and 480 ppm. To stay within these limits, an CO_2 eq. price of 80$ in 2020$ increasing to 200$ in 2050 is required. A lower tax of 19 USD in 2020 and increasing to 100 USD in 2050 will result in a 530- 580 ppm scenario according to the IPCC which would not be compatible with COP21 and EU climate goals.

Carbon tax scenario	2020 [USD/ton CO_2eq]	2030 [USD/ton CO_2eq]	2050 [USD/ton CO_2eq]	2100 [USD/ton CO_2eq]
Zero	0	0	0	0
Low	19	32	100	550
High	80	90	220	1500

Table 4.15: Carbon tax scenario's

4.11. Integral cost of fuel prices and carbon tax

To get insight into the competitive position of renewable version of a fuel compared to fossil version, the integrated prices of the fuel cost and carbon tax can be calculated. This is done using formula 4.9

$$\text{Fuel Cost}_{\text{integrated},i,j} = \text{Fuel price}_{i,j} + EF_i * CT_j \tag{4.9}$$

where:

$\text{Fuel price}_{i,j}$ = fuel price of fuel i in year j in USD/ton
EF_i = The emission factor of fuel i in CO_2 equivalent as calculated in chapter 3
CT_j = The carbon tax in year j

This gives insight into the total cost of using fossil and renewable fuels. An example of this shown in figure 4.5 for a low fuel price and 'high' carbon tax scenario. It can be seen that the cost of fossil fuels has increased significantly compared to the fuel prices as shown in figure 4.4 where no carbon tax was applied yet. The results for all combinations of fuel scenarios and carbon tax scenarios can be found in appendix A. It was found that generally renewable fuels will not be financially competitive with fossil fuels without a carbon tax. An exception on this is a 'best' fuel scenario around the year 2045, in which renewable ammonia is found to be as expensive to produce as fossil ammonia. The application of a carbon tax changes this significantly, making ammonia economically competitive abound 2032 for a 'high' carbon tax scenario with a 'best' fuel scenario.

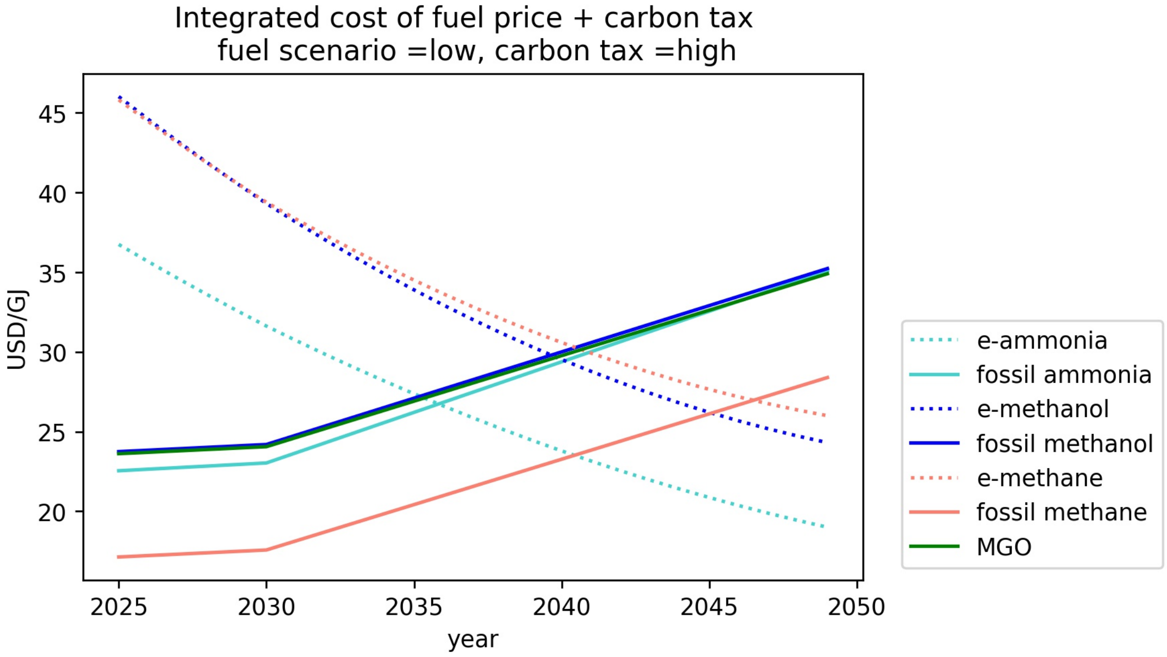


Figure 4.5: Caption

4.12. Conclusion

The goal of this chapter was to give an overview of renewable fuel types and to make an estimation of future renewable fuel prices for a 'high' and a 'low' fuel price scenario. Therefore the fuel production efficiencies of the selected renewable fuels were analysed

It was found that ammonia is more efficient to produce compared to methanol and methane, resulting in lower operational expenses during production. In combination with renewable power prices and capital expense estimations, fuel price estimations were made. It was found that on a USD/GJ bases, renewable ammonia is expected to be the most cost effective e-fuel to produce between 2025 and 2050. Meanwhile methane and methanol are expected to have higher production cost. Overall renewable fuel cost are expected to decrease as much as 50% for an ’high’ renewable energy scenario and up to 60% for a ’low’ renewable energy scenario between 2020 and 2050. This is a result of expected improvements in production efficiencies, decreasing capital cost and decreasing renewable power prices.

Finally the integral price of fuels was calculated by combining the carbon tax cost and fuel price of the fuels. Without a carbon tax renewable fuels are expected to be more expensive than the fossil fuel prices. However a carbon tax can improve the position of renewable fuels significant. with ’low’ renewable fuel prices and a high carbon tax, ammonia could already become economically competitive as early as 2030.

5

Models to analyse the selected scenarios

The research objective of this study is to gain better insight into the financial impact of using alternative fuels and speed reduction to comply with emission reduction regulation for a broad range of chemical tankers for several scenario's. Therefore three combinations of carbonation pathways and implementation strategies were selected in chapter 2.

To be able to analyse these three combinations of decarbonization pathways and implementation strategies, three models were developed. The first model is designed to analyse scenario 1 to 6, the second for scenario 7 to 12 and the last model to cover scenarios 13 to 18. The goal of this chapter is to explain the working of these models. Since these models share many aspects, it is chosen to first explain the model for scenario 1 to 6. Then it explained how this model is adjusted to be able to analyse scenario 7 to 12. Afterwards this model is then further developed into the model for scenario 13 to 18.

5.1. Model for scenario 1 to 6

The goal of this section is to explain the working of the model used to analyse scenario 1 to 6. Therefore an overview of the input variables of the model is first given in section 5.1.1. Next the rationale of the model is explained in paragraph 5.1.2. Finally paragraph 5.1.3 to 5.1.8 will explain the individual parts of the model. An overview of the model can be found in figure 5.1.

5.1.1. Input

To be able to build a tool that can analyse a broad range of chemical tankers, a model is created that can estimate the characteristics of a vessel depending on various variables. It is chosen to use such a model instead of using reference vessels because a parametric model can generate a matrix of vessels based on many variables, making broad analysis possible. Using reference vessels, it is extremely difficult to compare vessels that only differ on one variable such as design speed for example, complicating achieving the goal of this thesis, which is to find trends along different variable axes.

To be able to generate a large variety of vessel, deadweight has been chosen as the first input variable and will be used to determine the characteristics of the vessel.

The 'design speed' is the second input variable of the model. The installed power on a ship is mainly determined by the required propulsion power, which is a result of the hull resistance and the speed at which it the vessel sails. This makes the design speed an important variable.

The third variable is the 'trade distance' which is the distance from Harbor A to Harbor B, i.e. this is half a

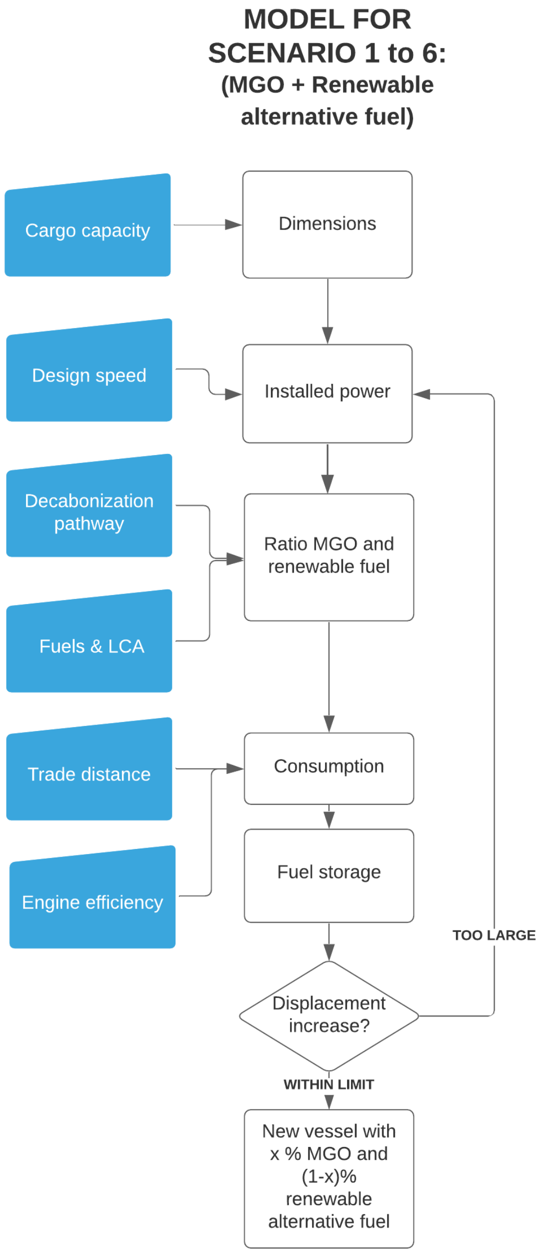


Figure 5.1: Overview of the parametric model for scenario 1 to 6

round trip distance. This is an important variable because it influences the required fuel capacity of the vessel and therefore also the deadweight.

The fourth variable ’fuels’ is the selection of alternative fuels. The objective of the project is to find trends along the use of alternative fuels by comparing different fuel types. The choice of fuel is a important variable because it has an impact on the main characteristics of the ship as storing alternative fuels can require more storage space and increase the weight of the fuel compared to the reference fuel. More weight influences the resistance and therefore the installed power.

Finally the ’Decarbonization pathway’ is the final variable, this is the regulation scenario to which the vessel should comply. This greatly influences the quantity of renewable fuel used on the vessel, which influences the design. This is therefore an important variable.

This gives the following list of variables:

- Cargo capacity
- Design speed
- Trade distance
- Fuels
- Decabonization pathway

5.1.2. Model architecture

These input variables are then used in the model as can be seen in figure 5.1. The purpose of the model is to be able to reconfigure a vessel for a decarbonization pathway in which the vessel operates with a 70% lower emission intensity. This achieved by adding an renewable alternative fuel to the MGO. This model can then by used to analyse abroad range of vessels with different design speeds. In this model, the carbon reduction needs to be achieved compared to the same vessel with the same design speed but operating on MGO.

To achieve this, the model first estimates the dimensions of a reference vessel for the provided cargo capacity. This is done in the block 'Dimensions'. The model then estimates the installed power of the vessel in the block 'Installed power'. In the block 'Ratio of MGO and renewable fuel' the model then estimates how much renewable fuel should be mixed in with the MGO to achieve the decarbonization target. Using the trade distance, installed power and the ratio of MGO and renewable fuel, the total fuel consumption is estimated in the block 'Consumption'. Using the fuel consumption, the required storage capacity is then estimated in the block 'fuel storage'. This block also estimated the weight of the fuel storage and fuel itself. If fuel storage and fuel lead to change in displacement larger than 0.0001% then the model goes back to the 'installed' power block and makes a recalculation of the installed power. This then also requires a recalculation of the ratio of MGO and renewable fuel. Because the installed power has increased, the vessel will have to increase its share of renewable fuel to keep compliant with the decarbonization goal. This again influences the storage and so on until there is a converged solution.

5.1.3. Dimensions

The first step of the model is to estimate the dimensions of the vessel based on the deadweight of the vessel. This is done based on the formula's as further explained below. The fact that this method is not able to take design constrains into account, for the Panama canal for example, is accepted.

The length overall of a chemical tanker is first estimated using equation 5.1[53]

$$L_{oa} = \frac{ln\left(\frac{50 \cdot dwt}{18491}\right)}{0.0258} \tag{5.1}$$

The length between perpendiculars can then be estimated using equation 5.2. This formula is based on a regression performed on data obtained from Clarksons, as can be seen in appendix B.

$$L_{pp} = 1.0029 \cdot L_{oa} - 8.4414. \tag{5.2}$$

The width is calculated using equation 5.3[53]:

$$B = 0.125 \cdot L_{oa}^{1.0445} \tag{5.3}$$

For the draft of the vessel, equation 5.4 is used. This formula is based on a regression performed on data obtained from Clarksons, as can be seen in appendix B

$$T = 0.0676 \cdot L_{oa}^{0.9877} \tag{5.4}$$

The displacement is calculated using the block coefficient. This coefficient C_B is calculated using equation 5.5[70]. Where f is 1.06 for chemical tankers.

$$C_B = 0.8217 \cdot f \cdot L_{pp}^{0.42} \cdot B^{-0.3072} \cdot T^{0.1721} \cdot V^{-0.6153} \tag{5.5}$$

For V in this equation, the average design speed ($V_{\text{average design}}$) of the chemical tanker of that size is used. This speed is the speed that a vessel of that size can be expected to normally operate on. This average design speed can be calculated using equation 5.6[67]. This formula has a maximum of 15 knts.

$$V_{\text{average design}} = 5.8343 \cdot dwt^{0.0982} \qquad for\ R : [13 : 15] \tag{5.6}$$

The displacement in tons is then calculated using equation 5.7, where ρ is the density of water, set at 1.025.

$$\Delta = L_{pp} \cdot B \cdot T \cdot C_B \cdot \rho \tag{5.7}$$

5.1.4. Installed power

The second step in the model is to estimate the installed power of the chemical tanker. This can be done using more advanced empirical methods such as a Holtrop-Mennen analysis or by using more simply methods such as the Admirality constant. The latter is only able to give an approximate idea about the required power, which is mainly suited for preliminary design phase of a vessel. Since this study also looks at the general characteristic of a vessel, and not at the in detail characteristics, it has been chosen to use the the Admiralty constant to determine the power requirements. The formula for this can be seen in equation 5.8.

$$P_{\text{inst}} = \frac{\Delta^{2/3} \cdot V^3}{C_{\text{adm}}} \tag{5.8}$$

Where Δ is the displacement in tons, V is the vessel speed and C is a vessel specific constant.

To be able to use this method, the Admiralty constant for the chemical tanker with a certain displacement needs to be determined. This is done using equation 5.9.

$$C_{\text{admi}} = \frac{\Delta^{2/3} \cdot V^3_{\text{average design}}}{P_{\text{installed, average design speed}}} \tag{5.9}$$

The design speed required for this equation can be calculated using formula 5.6. The installed power in kW of a vessel with average design speed ($V_{\text{average design}}$) and a deadweight can be determined using equation 5.10[46].

$$P_{\text{inst, average design speed}} = 22.419 \cdot dwt^{0.5595} \tag{5.10}$$

This gives all the required information to determine the Admiralty constant for a chemical tanker with capacity Q. This can then be used to determine the installed power for a chemical tanker with the same capacity but a different design speed. Furthermore this method also enables for a correction to the installed power if the model concludes that the displacement has increases due to the use of the new fuel as can be seen in equation 5.11

$$P_{\text{inst.,corr.}} = \frac{\Delta_{corr.}^{2/3} \cdot V^3}{C_{\text{adm}}} \tag{5.11}$$

5.1.5. Ratio MGO and renewable fuel

Now the dimensions and installed power is determined, the next step is to calculate the required fraction fraction of renewable fuel. The vessel needs to reduce its carbon intensity by 70% for the decarbonization pathway in scenario 1 to 6. This is 70% compared to same chemical tanker, designed at the same design speed but powered by MGO. To determine the fraction of renewable fuel, the relative emission factor (REF) of the fuels is used. This factor is an indicator for the relative emissions associated with one MJ of fuel energy for

Fuel	**Relative emission factor (REF) measured on LCA bases**
MGO	1.000000
Fossil methane	0.997183
Renewable methane	0.231454
Fossil ammonia	1.111279
Renewable ammonia	0.088406
Fossil methanol	1.017327
Renewable methanol	0.097342

Table 5.1: Relative life cycle emission of all fuel compared to MGO for the same amount of thermal energy. This is based on the results of chapter 3.

a fuel compared to MGO. The REF of all fuels considered in this study can be found in table 5.1. These values are based on the life cycle analysis performed in chapter 3.

The renewable fuel fraction is determined by solving equation 5.12

$$(1 - RT) \cdot (P_{\text{inst}} \cdot REF_{\text{MGO}}) = P_{\text{inst,corr.}} \cdot (\text{Fr}_{\text{MGO}} \cdot REF_{\text{MGO}} + \text{Fr}_{\text{ren.}} \cdot REF_{\text{ren.}}) \tag{5.12}$$

Where:

P_{inst} = the installed power of the MGO powered version of the vessel.
$P_{inst,corr.}$ = the installed power of the new configuration
RT = The reduction target, for example 0.7 for a 70% emission reduction
REF_{MGO} = The relative emission factor of MGO
$REF_{ren.}$ = The relative emission factor of the renewable fuel.
Fr_{MGO} = The fraction of energy generated from MGO
$Fr_{Ren.}$ = The fraction of energy generated from the renewable fuel.

Minimal pilot fuel

The equation above provides a fraction of the energy that needs to be provided by the renewable fuel to comply with the pathway. It could be the result of equation 5.12 that a very large part needs to be replaced with renewable fuel. However for each of the alternative fuels, a minimal amount of MGO is needed as pilot fuel. Therefore a feasibility check is needed for every result of formula 5.12.

It was found that for methanol a minimum of 5% of fuel mass is required as pilot fuel[61]. This is needed because methanol is more difficult to ignite compared to diesel due to its higher auto-ignition temperature. Similar to methanol, ammonia also requires a pilot fuel. This is tested for multiple diesel-ammonia ratio's in research and it found that the engine could be operated up to a maximum weight share ratio of 95% ammonia and 5% diesel. Therefore a minimum of 5% mass diesel will be used in this study[55][18]. For LNG a pilot fuel energy percentage of 2.5% diesel is assumed[18]. These values can also be seen in table 5.2

Fuel	Minimal Pilot fuel [%]
MGO(pilot)	0
Methanol	5% of mass = 10.14% of energy
Ammonia	5% of mass = 10.7% of energy
LNG	2.5% of mass = 2.18% of energy

Table 5.2: Minimal pilot fuel percentages

5.1.6. Fuel consumption

Next step is to determine the fuel required fuel capacity. It is assumed that the chemical tankers are all outfitted with a two stroke engine[18]. Two stroke, low speed turbocharged diesel engines generally exhibiting 50% thermal efficiency according to Grljušić et al[32] and this efficiency will be used in this study for the MGO engine. Wärtsilä states that the efficiency of Wärtsilä dual-fuel diesel and gas engines have increased steadily over the years and efficiencies up to 50% can be achieved [72]. The thermal efficiency of two stroke dual fuel LNG engines is therefore set at 50%.

For ammonia a thermal efficiency of 50% will also be used. This is based on the claim made by MAN Energy Solution that their engines can "operate on almost any fuel or fuel quality with no or limited decrease in efficiency and with the reliable performance and operating characteristics as the conventional two-stroke engine even in adverse weather conditions.[63]" For methanol a identical thermal efficiency will be used[4].

The fuel consumption on the vessel can then be estimated based on the engine efficiency, trade distance and installed power. It is assumed that design speed it achieved at 85% of the MCR, so en engine margin (EM) of 15% is assumed. The formula for the MGO can be seen in equation 5.16 and in equation 5.17 for the renewable fuel:

$$FC_{MGO} = \frac{\text{Distance}_{round,trip} \cdot 60 \cdot 60 \cdot (1-\text{EM}) \cdot P_{inst.corr} \cdot Fr_{MGO}}{\eta_{comb} \cdot V_{design} \cdot \text{Mass energy density}_{MGO}} \tag{5.13}$$

$$FC_{Ren} = \frac{\text{Distance}_{round_{t}rip} \cdot 60 \cdot 60 \cdot (1-\text{EM}) \cdot P_{inst.corr} \cdot Fr_{Ren}}{\eta_{comb} \cdot V_{design} \cdot \text{Mass energy density}_{Ren}} \tag{5.14}$$

FC_{MGO} = Fuel consumption of MGO on a round trip in kg
FC_{Ren} = Fuel consumption of a renewable fuel on a round trip in kg
Fr_{MGO} = The fraction of energy generated from MGO
$Fr_{Ren.}$ = The fraction of energy generated from the renewable fuel.
η_{comb} = The combustion efficiency
EM = The engine margin
V_{design} = The design speed
$\text{Distance}_{roundtrip}$ = Distance of a round trip in nautical miles
$P_{inst,corr}$ = The installed power

5.1.7. Fuel storage

Having determined the fuel consumption of both the the MGO and renewable fuel, next the amount of fuel capacity of the vessel is calculated. This is done based on three parameters. The first is the energy demand of the vessel for a single round trip. Secondly 10% additional fuel capacity is added to compensate for the non retrievable fuel in the tanks. Thirdly additional capacity is added to provide some flexibility and to cover for additional fuel consumption in bad weather. This extra capacity is primarily a choice of the ship owner and can be a matter of business strategy. Adding extra capacity allows the operator to bunker more fuel at locations with lower bunker prices which can be financially attractive. However this study will limit the extra capacity since alternative fuels require more volume than conventional fuels. The additional capacity is therefore set at 25%.

$$\text{Fuel capacity}[kg] = \text{Fuel consumption} \cdot (1 + C_{\text{non retrievable}}) \cdot (1 + C_{\text{extra capacity}}) \tag{5.15}$$

Where:

$C_{nonretrievable}$ = The fraction of non retrievable fuel
$C_{extracapacity}$ = The fraction fuel taken as extra capacity

Methanol storage

Methanol is a liquid at standard ambient temperature and pressure(SATP), which means that methanol storage tanks do not require insulation, pressure or cooling. This is a major advantage compared to other alternative fuels such as ammonia or hydrogen that need refrigeration, compression or a combination of both. This result in a more efficient use of storage space due to the absence of insulation and offers more flexibility in the selection of storage locations within the vessel[71].

The methanol fuel storage system requires special attention when it comes to the location of fuel tanks in line with the IGF code. Because methanol is a low-flashpoint fuel, it requires a protective cofferdam at all locations where the tanks are not bounded by bottom shell plating of the ship. A perk of methanol is that methanol can be stored in double bottom tanks because it considered to be not harmful to the environment.[52][35]. Overall it is assumed that methanol does not require significant changes to the vessel and can be implemented into the vessel.

Ammonia storage

Ammonia can also be stored at atmospheric pressure if refrigerated to temperatures below -33.6 C°or under pressure without refrigeration[56][51]. Large downsides of semi and fully refrigerated storage are the required back-up systems and insulation. These must be in place to make the arrangement sufficiently reliable to ensure continuous low temperature (and hence pressure) in the tank. The anticipated choice for storing ammonia for use as propulsion fuel is therefore likely to be a pressurized tank type C at ambient temperature according to DNV GL[56]. This because this is a more reliable and simple solution compared to refrigerated or semi-refrigerated storage. The requirements for the location of the tanks and fuel pipes are expected to be similar to the DNV GL requirements for LPG fuel[56]. This includes a minimum distance from ship sides and bottom to limit the risk of tank rupture when suffering damage. The tank location must be away from high fire risk spaces and engine rooms, and it should be protected from areas with a high damage risk such as the surrounding of crane[56]. Overall it is assumed that ammonia can be stored on deck without changes to the vessel dimensions. This location could marginalises the stability of a vessel however stability calculations fall outside the scope of this study.

LNG storage

The C-Tank type is the most common tank technology for LNG fuel containment and is produced for smaller scale applications such as fuel storage. Their main characteristic is the high storage pressure gas, approximately 5 bar, and a maximum allowable working pressure of 20 bar[22]. Locating LNG fuel tanks on deck is presently done on vessels and this study will also assume that this is possible[22].

Storage system weight

Next the weight of the tanks needed to store the fuels is calculated. The weight of the fuel storage system is estimated based on the parameters as found in table 5.3.

Fuel	**MGO**	**LNG**	**MeOH**	**NH3**
Tank weight[kg/kg fuel]	0.00	0.29	0.00	0.47
Energy density LHV [MJ/kg]	42.7	49.7	19.9	18.6
Energy denisty LHV incl. tank [MJ/kg]	42.7	38.7	19.9	12.6

Table 5.3: The weight of fuel storage[14]

From this the total weight of fuel and tanks can be determined. This can then be used to calculate the new displacement of the vessel. If that displacement increases more than 0.0001%, then the installed power is recalculated using the new displacement.

5.1.8. Exhaust Gas Treatment

Ammonia is a carbon and sulphur free fuel, and combustion therefore produces no CO_2 or SO_x emissions and negligible amount of soot. Exhaust gasses from the combustion of ammonia do contain other pollutants such as NO_x and N2O and possible slip of ammonia. Due to these emissions, ammonia fuelled ships might not comply with Tier III and therefore will require treatment of exhausts gasses to reduce the NOx byproducts. A possible solution is selective catalytic reduction (SCR) technology, which is a mature technology that is already in use on vessels. SCR is an exhaust gas after-treatment process where a catalytic reduction is used to remove NO_x and N2O from the exhaust gas[44].Normally ammonia is used as the reducing agent by adding an urea solution into the exhaust gas, however direct injection of ammonia is possible as can be seen in figure 5.2. A perk of this after-treatment technology is that a ammonia-fuelled ship already carries the required ammonia. According to MAN Energy Solutions, the ammonia consumption for the SCR system is small compared to ammonia used for propulsion[63].

For methanol it is assumed that an SCR is needed[18].

For the diesel fuelled reference engine NO_x, it is assumed that an SCR is needed to be able to meet NO_x Tier III levels[4].

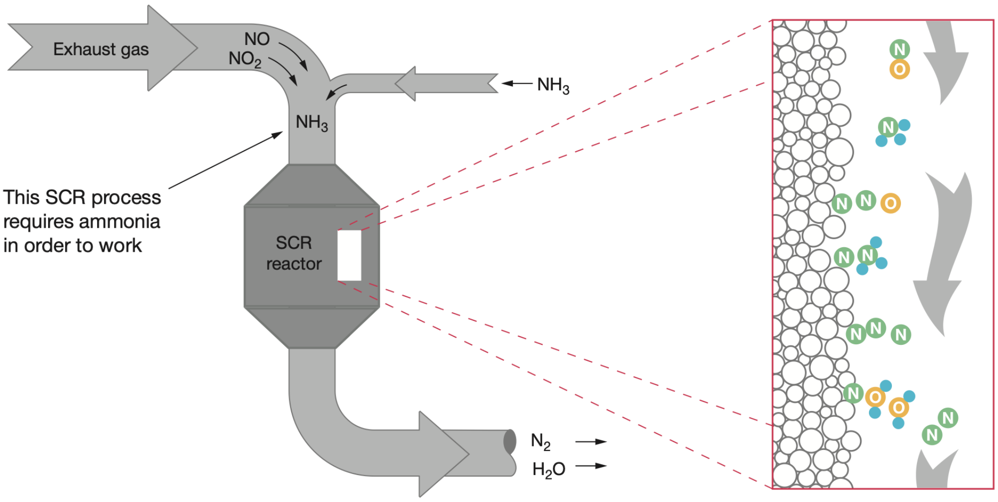


Figure 5.2: The selective catalytic reduction process[63]

5.2. Model for scenario 7 to 12

This section will explain the model that is used to analyse scenario 7 to 12. The decarbonization pathway in scenario 7 to 12 is a gradual implementation of IMO goals. This pathway requires a continuous improvement of the carbon intensity over the years, with 2008 as reference point. A reduction of 40% should be achieved in 2030 and a emission intensity reduction of 70% in 2050. The annual emission reduction goals are assumed to follow a linear line between the set targets in 2008, 2030 and 2050. In scenario 7 to 12 the emission intensity reduction needs to be achieved compared to the same vessel with the same speed but then operating on MGO.

The technical solution chosen for these scenario's is a complete switch to an alternative fuel except a minimal pilot fuel. To be able to achieve its carbon goals, the vessel can then operates on a combination of the fossil and renewable version of the alternative fuel. As regulation becomes stricter over the years, the vessel can increase its share of renewable fuel to keep compliant.

To analyse scenario 7 to 12 a new model is developed that is built of from two sub-models. The first model a parametric model to determine the impact of the complete switch to an alternative fuel (plus minimal pilot fuel), this model will be explained in paragraph 5.2.1. The second sub-model is the 'yearly bunker model. This model determines how much renewable fuel is required each year to keep compliant with the decarbonization goals. Paragraph 5.2.2 will explain this model further.

5.2.1. Parametric model for scenario 7 to 12

The parametric model used to analyse scenario 7 to 12 is for a large part similar to the model used for scenario 1 to 6. An overview of this model can be seen in figure 5.3 The 'inputs', the block 'dimension' and the block 'installed power' are identical to those blocks in the model for scenario 1 to 6. For further information on these blocks, paragraph 5.1.1, 5.1.3 and paragraph 5.1.4 can be consulted.

Fuel consumption

The first difference compared to the model for scenario 1 to 6 occurs at the block "fuel consumption". In the model for scenario 7 to 12, a complete switch to alternative fuel is made with the exception of the pilot fuel. Because the type of alternative fuel (renewable or fossil) does not influence the design of the vessel, it is now possible to directly estimate the fuel consumption of the vessel based on several parameters. These are engine efficiency (see paragraph 5.1.6 explanation), trade distance, installed power and minimal pilot fuel.

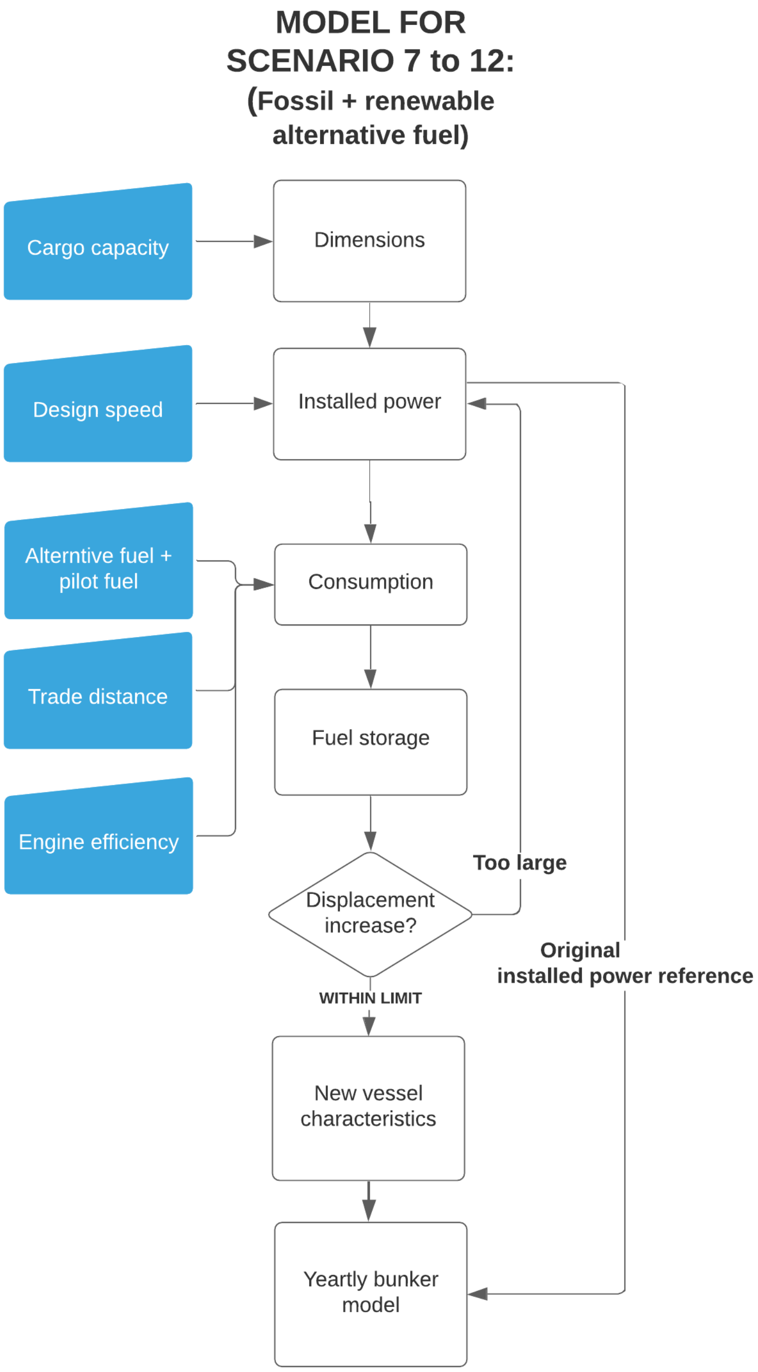


Figure 5.3: Caption

Again it is assumed that design speed it achieved at 85% of the MCR. The formula for the fuel consumption of the pilot and alternative fuel can be seen in respectively equation 5.16 and 5.17:

$$FC_{pilot} = \frac{\text{Distance}_{round,trip} \cdot 60 \cdot 60 \cdot (1 - \text{EM}) \cdot P_{inst.corr} \cdot Fr_{pilot}}{\eta_{comb} \cdot V_{design} \cdot \text{Mass energy density}_{pilot}} \tag{5.16}$$

$$FC_{Alt} = \frac{\text{Distance}_{round_{t}rip} \cdot 60 \cdot 60 \cdot (1 - \text{EM}) \cdot P_{inst.corr} \cdot (1 - Fr_{pilot}}{\eta_{comb} \cdot V_{design} \cdot \text{Mass energy density}_{Ren}} \tag{5.17}$$

FC_{pilot} = Fuel consumption of pilot fuel(MGO) on a round trip in kg
FC_{Alt} = Fuel consumption of the alternative fuel on a round trip in kg
Fr_{pilot} = The fraction of energy generated from MGO
η_{comb} = The combustion efficiency
EM = The engine margin
V_{design} = The design speed
$\text{Distance}_{roundtrip}$ = Distance of a round trip in nautical miles
$P_{inst,corr}$ = The installed power

Next the fuel capacity (fuel storage in overview) can be determined as is done for the model for scenarios 1 to 6. If the displacement has increased more than 0.0001% due to the stored fuel and associated tanks, the installed power will be recalculated using the Admiralty constant as was also done in the model for scenario 1 to 6. Again this continues until the model converges to a solutions. From this then follows a vessel operating on the alternative fuel with new characteristics, which was the purpose of the parametric model.

5.2.2. Yearly bunker model

The next step is to determine how much fossil alternative fuel and how much renewable alternative fuel is used each year. To find the optimal ratio between the two for each year that the vessel is in operation, a model is developed of which an overview can be seen in figure 5.4. The model has will determine the combination of fuels based on three parts that are further explained below:

- **Part 1 - Pilot fuel:** The vessel requires a minimal amount of pilot fuel as has been determined by the parametric model, hence this value is not changed by the bunker model.
- **Part 2 - Renewable alternative fuel to comply with IMO:** Next a minimum amount of renewable alternative fuel is needed to comply with the decarbonization pathway that becomes stricter every year.
- **Part 3 - Fossil or renewable alternative fuel:** Finally a part of the fuel taken can be filled by either renewable or fossil alternative fuel. If this part is filled by renewable fuel than the vessel operates with less emissions than IMO goal require. If this part is filled with fossil alternative fuel than the vessel operates just complying with the IMO goals.

The first part is determined by the parametric model because the amount of pilot fuel is a fixed value. The second part can be found by solving equation 5.18

$$(1 - RT) \cdot (P_{\text{inst}} \cdot REF_{\text{MGO}}) = P_{\text{inst,corr.}} \cdot (\text{Fr}_{\text{Pilot}} \cdot REF_{\text{Pilot}} + \text{Fr}_{\text{ren}} \cdot REF_{\text{ren}} + \text{Fr}_{\text{fos}} \cdot REF_{\text{fos}}) \tag{5.18}$$

Where:

P_{inst} = the originally installed power on the MGO powered reference version of the vessel.
$P_{inst,corr}$ = the installed power of the new configuration
RT = The reduction target for a specific year, for example 0.7 for a 70% emission reduction
REF_{Pilot} = The relative emission factor of the pilot fuel (MGO)
REF_{ren} = The relative emission factor of the renewable version of the alternative fuel.
REF_{fos} = The relative emission factor of the fossil version of the alternative fuel.
Fr_{Pilot} = The fraction of energy generated from the pilot fuel(MGO)
Fr_{Ren} = The fraction of energy generated from the renewable version of the alternative fuel.
Fr_{fos} = The fraction of energy generated from the fossil version of the alternative fuel.

The last part (Part 3) is filled according to the most financially attractive solution. To determine this, the model uses the integrated cost of the fuel price and carbon tax. This is the addition of the fuel price and the carbon tax that has to paid after to burning the fuel in question. Depending on the fuel prices and carbon tax applying in a specific year, the overall cost of one of the two will be lower. The fuel with the lowest overall cost is then selected to fill in part 3.

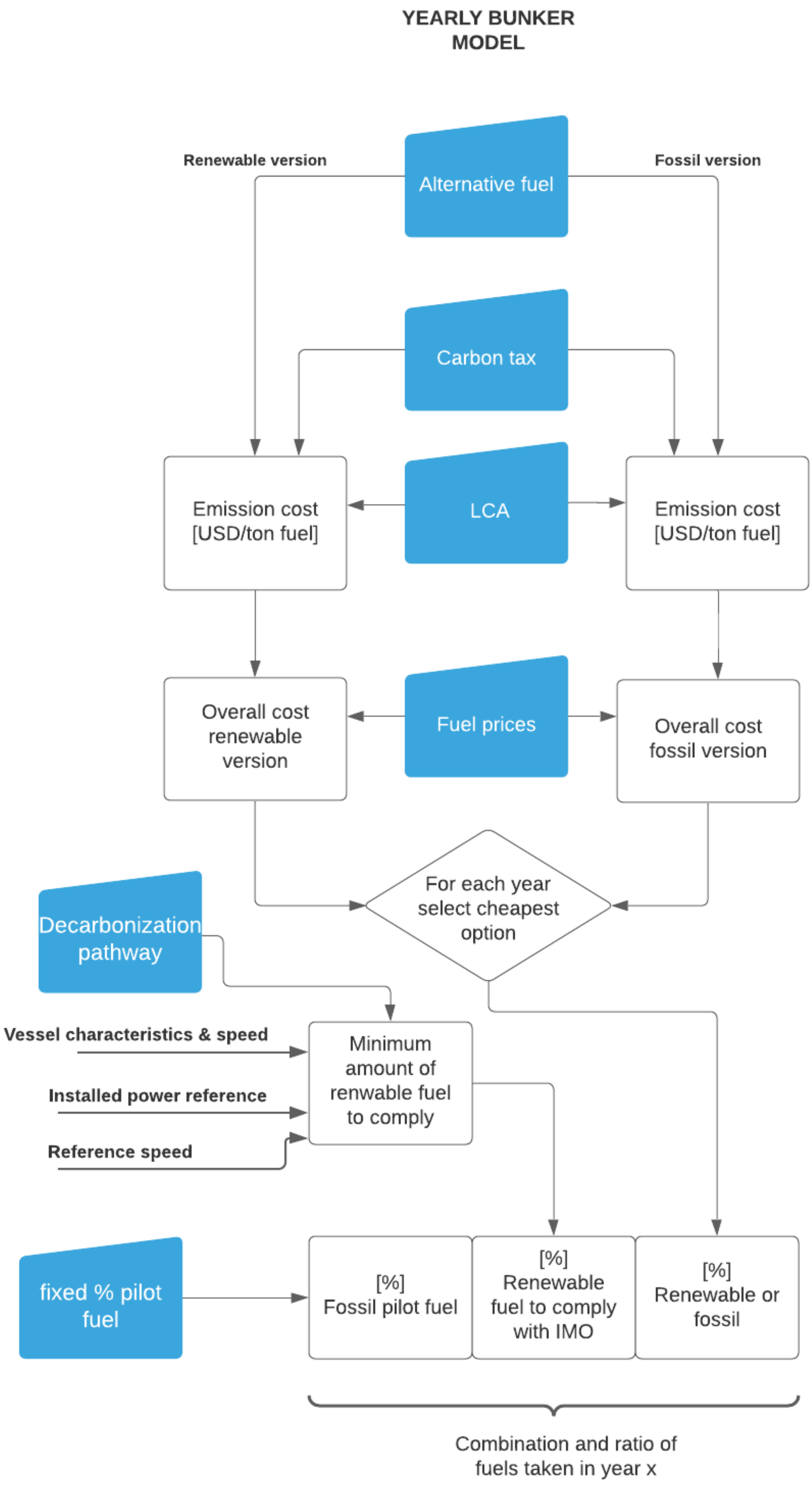
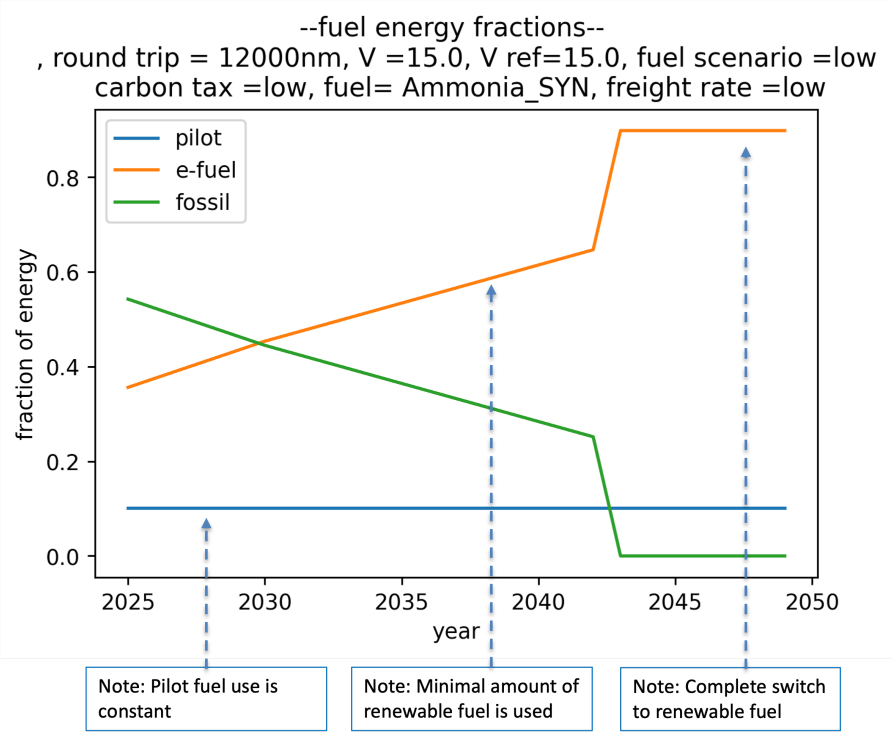


Figure 5.4: Overview of the yearly bunker tool



Note: Pilot fuel use is constant

Note: Minimal amount of renewable fuel is used

Note: Complete switch to renewable fuel

Figure 5.5: An example of the fuel use on a ammonia fuelled 45000 tons chemical tanker on a trade of 12000nm round trip. Design speed is 15 knts. The scenario depicted is scenario 10 from the research scenario overview in chapter 2, with a low carbon tax and low renewable fuel prices. It can be seen that between the year 2025 and 2042 a minimal amount of renewable fuel is used. Then a complete switch is made to renewable fuels in 2042. This can explained by looking at the combination of carbon taxes and fuel prices for this scenario.

This model can result in a very varying use of alternative fuels over the years. To illustrate how the models works, figure 5.5 is shown below. This figure shows the fractions of the pilot, renewable and fossil alternative fuel over the years. This distribution belongs to a ammonia fuelled 45000 tons chemical tanker on a trade of 12000nm round trip. Design speed is 15 knts. The scenario depicted is scenario 10 from the research scenario overview in chapter 2, with a low carbon tax and low renewable fuel prices. It can be seen that between the year 2025 and 2042 a minimal amount of renewable fuel is used. This is to keep compliant with the decarbonization pathway. Then a complete switch is made to renewable fuels in 2042. This can explained by looking at the combination of carbon taxes and fuel prices for this scenario in figure A.4 in Appendix A. There it can indeed be seen that it is cheapest solution to use renewable methanol in the year 2042 and on.

5.3. Model for scenario 13 to 18

The third model used in this study is developed to analyse scenario 13 to 18.The decarbonization pathway in scenario 13 to 18 is a gradual implementation of IMO goals. This pathway requires a continuous improvement of the carbon intensity over the years, with 2008 as reference point. A reduction of 40% should be achieved in 2030 and a emission intensity reduction of 70% in 2050. The annual emission reduction goals are assumed to follow a linear line between the set targets in 2008, 2030 and 2050.

The technical solution chosen for these scenario's is a combination of

- Speed reductions
- A complete switch to an alternative fuel except a minimal pilot fuel.

To be able to achieve its carbon goals, it can be chosen for the vessel to be designed and operate on a lower speed compared to the reference speed at which a such vessels 'normally ' operates. It is assumed that the vessel operates at a constant speed during its lifetime. Suppose the reference speed for a vessel is 20 knots, then the new vessel can be designed at 14 knots to reduce the carbon intensity. This concept is also known as 'slow steaming'. In addition the vessel can operate on a combination of the fossil and renewable version of the alternative fuel to mitigate emissions. As regulation becomes stricter over the years, the vessel can increase its share of renewable fuel to keep compliant. It is important to note that in this model the emission intensity reduction needs to be achieved compared to the a vessel with the same capacity, operating at a predetermined fixed reference speed. That way the influence of speed reduction can be analysed later on.

To analyse scenario 13 to 18 a new model is developed that is again built of from two sub-models. The first model a parametric model to determine the impact of the complete switch to an alternative fuel (plus minimal pilot fuel), this model will be explained in paragraph 5.3.1. The second sub-model is the 'yearly bunker model. This model determines how much renewable fuel is required each year to keep compliant with the decarbonization goals. Paragraph 5.2.2 will explain the purpose and goal of this model.

5.3.1. Parametric model for scenario 13 to 18

The parametric model used to analyse scenario 13 to 18 is almost the same as the model used for scenario's 7 to 12. An overview of the model can be seen in figure 5.6. The one exception is the block 'installed power reference vessel' which can be found at the right side of the model overview. This block calculates the installed power for the vessel that is being analysed, but is designed to operate at the 'reference speed'.

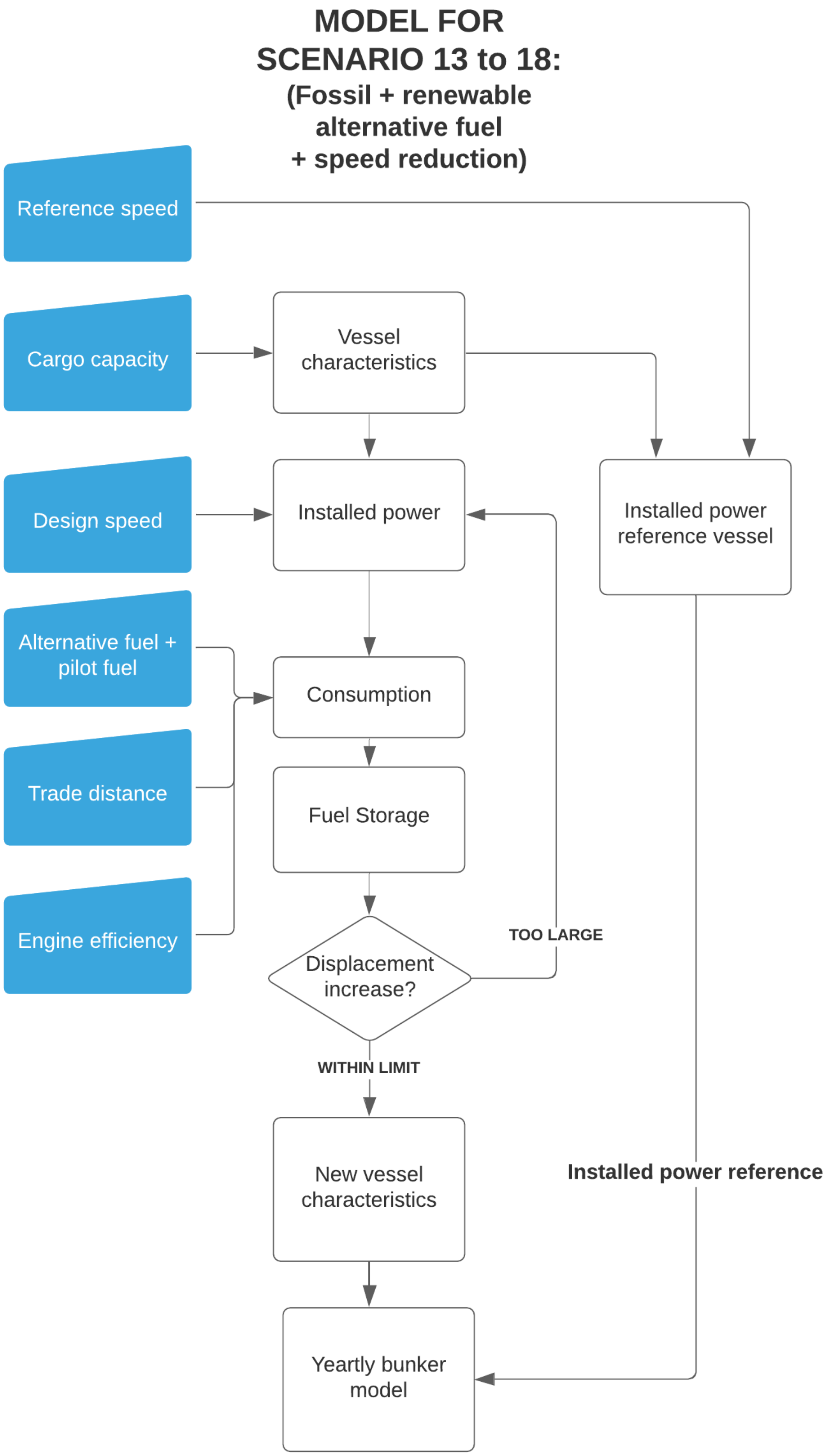


Figure 5.6: Caption

5.3.2. Yearly bunker Model

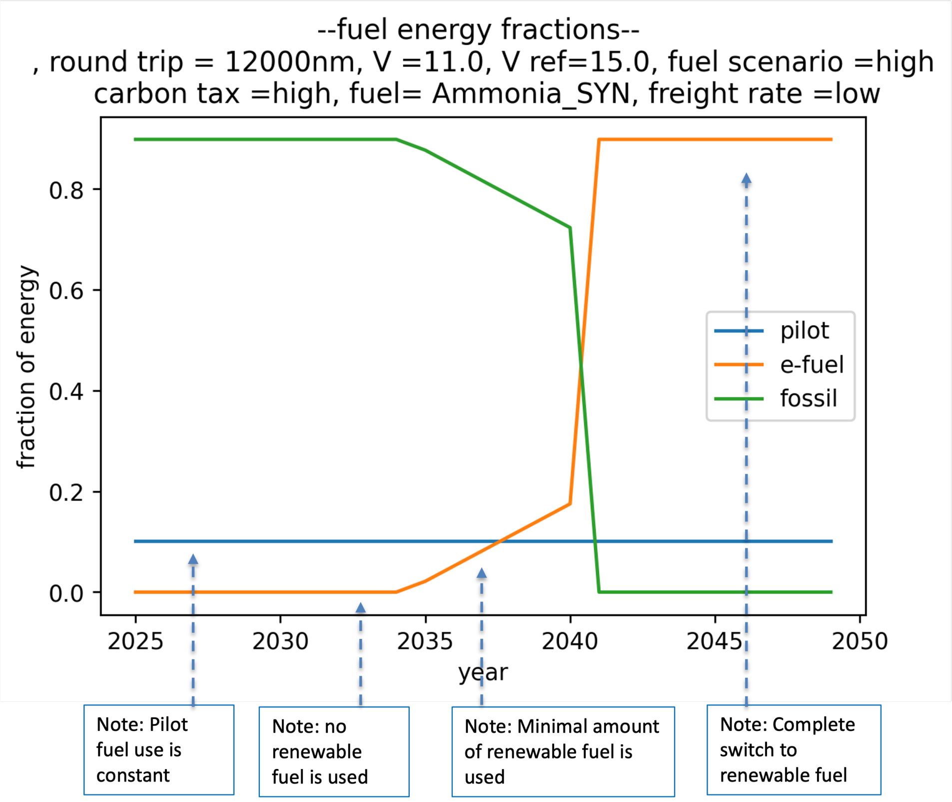
For scenario 13 to 18, one minor modification need to be made to the bunker tool compared to the tool used for scenario 7 to 12. The 'yearly bunker tool' used equation **??** to determine the amount of renewable fuel needed to comply with the decarbonization pathway in scenario 7 to 12. For these scenario's the speed of the reference vessel was the same as for the design vessel. For scenario 13 to 18, a reference speed was introduced to be able to analyse the influence of speed reductions. This changes the equation that determines the minimum amount of renewable fuel for a specific year. The new equation can be found in equation 5.19.

$$(1-RT)\cdot\left(\frac{P_{\text{inst,corr}}\cdot Dist}{V_{design}}\right)\cdot REF_{\text{MGO}} = \left(\frac{P_{\text{inst,ref.}}\cdot Dist}{V_{ref}}\right)\cdot(\text{Fr}_{\text{Pilot}}\cdot REF_{\text{Pilot}}+\text{Fr}_{\text{ren}}\cdot REF_{\text{ren}}+\text{Fr}_{\text{fos}}\cdot REF_{\text{fos}}) \tag{5.19}$$

Where:

$P_{inst,ref}$ = The installed power on the MGO powered reference vessel with reference speed V_{ref}.
$P_{inst,corr}$ = The installed power of the new vessel
$Dist$ = The distance of the trade
RT = The reduction target for a specific year, for example 0.7 for a 70% emission reduction
V_{design} = The design speed of the new vessel.
$V_{reference}$ = The speed of the reference vessel.
REF_{Pilot} = The relative emission factor of the pilot fuel (MGO)
REF_{ren} = The relative emission factor of the renewable version of the alternative fuel.
REF_{fos} = The relative emission factor of the fossil version of the alternative fuel.
Fr_{Pilot} = The fraction of energy generated from the pilot fuel(MGO)
Fr_{Ren} = The fraction of energy generated from the renewable version of the alternative fuel.
Fr_{fos} = The fraction of energy generated from the fossil version of the alternative fuel.

The effects of how this model influences the fuel use can be seen in figure 5.7. This figure shows the fuel use on a ammonia fuelled 45000 tonschemical tanker on a trade of 12000nm round trip. Design speed is 11 knts, while the reference speed is 15 knts. The scenario depicted is scenario 17 from the research scenario overview in chapter 2, with a high carbon tax and high renewable fuel price. It can be seen that between the year 2025 and 2043 no renewable fuel has to be used. This can be explained by the significant speed reductions, which lowers the carbon intensity of transport. Next between 2045 and 2039, a minimal amount of renewable fuel is used. In these years, the speed reduction is not sufficient to comply with the decarbonization pathway. Then a complete switch is made to renewable fuels in 2041. This can explained by looking at the combination of carbon taxes and fuel prices for this scenario in figure A.5 in Appendix A. There it can indeed be seen that it is cheaper to use renewable methanol in the year 2041 and on then to use fossil methanol.



Note: Pilot fuel use is constant

Note: no renewable fuel is used

Note: Minimal amount of renewable fuel is used

Note: Complete switch to renewable fuel

Figure 5.7: This figure shows the fuel use on a ammonia fuelled 45000 tons chemical tanker on a trade of 12000nm, round trip. Design speed is 11 knts, while the reference speed is 15 knts. The scenario depicted is scenario 17 from the research scenario overview in chapter 2, with a high carbon tax and high renewable fuel price. It can be seen that between the year 2025 and 2034 no renewable fuel has to be used. This can be explained by the significant speed reductions, which lowers the carbon intensity of transport. Next between 2034 and 2040, a minimal amount of renewable fuel is used. In these years, the speed reduction is not sufficient to comply with the decarbonization pathway. Then a complete switch is made to renewable fuels in 2041. This can explained by looking at the integrated cost of carbon taxes and fuel prices for this scenario in figure A.5 in Appendix A. There it can indeed be seen that it is cheaper to use renewable ammonia in the year 2041 then to use fossil ammonia.

6

Economic analysis

This section will explain how the financial analysis of the vessel is performed. Therefore the financial indicators will be explained in subsection 6.0.1. Next in subsection 6.0.2 the calculations behind the capital cost of a vessel will be explained. Afterwards subsection 6.0.4 will explain the calculations behind the operational cost of the vessel. Finally the formula's behind fuel cost and carbon tax cost are explained in respectively subsections 6.0.5 and 6.0.6.

6.0.1. Financial indicators

The final goal of this research project is to be able to determine the financial impact of alternative fuels on a specific trade. A common method to assess the financial impact is to determine the increase in Total cost of ownership (TCO). This approach can also be found in research performed by Baldi et al.[5] which researches the cost of alternative fuels for different types of vessels. The model limits the GHG emissions at a maximum level and then minimises the total costs of ownership (TCO). Using the TCO as a measure for the economic performance of a vessel is also used in similar research performed by J. tijdgat[66], J.M. Rozendaal[57], Bergsma[8] and Mestemaker et al.[47]. This research project will therefore also use the increase in TCO as a financial measure. The reference TCO used in these calculation is the TCO of the vessel when operating on MGO. The total cost of ownership can be calculated by formula 6.1[5].

$$\text{TCO} = (\text{CAPEX} + \text{OPEX} + \text{Fuel Cost} + \text{Carbon Tax}) \tag{6.1}$$

6.0.2. CAPEX

The calculation for the capital costs(CAPEX) will be explained in this section. The CAPEX depends on the initial building cost, how the ship is financed, depreciation, interest and scrap value. The formula for CAPEX is shown in equation 6.0.2. The crap value of the vessel will be set at 10%[66], the interest rate at 7% and the loan duration at the lifetime of the vessel (25 years)[45].

$$CAPEX = \left[\frac{r \cdot n}{1-((1+r)^{-n})}\right] \cdot C_{building} - \frac{C_{scrap}}{(1+r)^n} \tag{6.2}$$

Where:

n = Loan duration
p = principal payments
r = interest rate
$C_{building}$ = Building costs
C_{scrap} = Scrap value

The building costs $C_{buidling}$ of the vessel will be based on the building costs of conventionally fuelled reference vessels after which a correction is done for the use of an alternative fuel as can be seen in formula 6.3. Systems that are taken into account in the correction are the engine, fuel storage and after treatment.

$$C_{\text{building,new fuel}} = C_{\text{building,original}} - C_{\text{storage,original}} + C_{\text{storage,new}} - C_{\text{engine,original}} + C_{\text{engine,new}} + C_{\text{scrubber}} \tag{6.3}$$

6.0.3. New built cost

The building cost ($C_{building,original}$) of an chemical tankers is based on the trendline as can be seen in figure 6.1 and formula 6.4. This trendline depicts the building cost as function of the deadweight of the vessel and is based on data obtained from Clarkson.

$$\text{New built cost } [\$] = 0.0846 \cdot \text{dwt}^{0.5939} \tag{6.4}$$

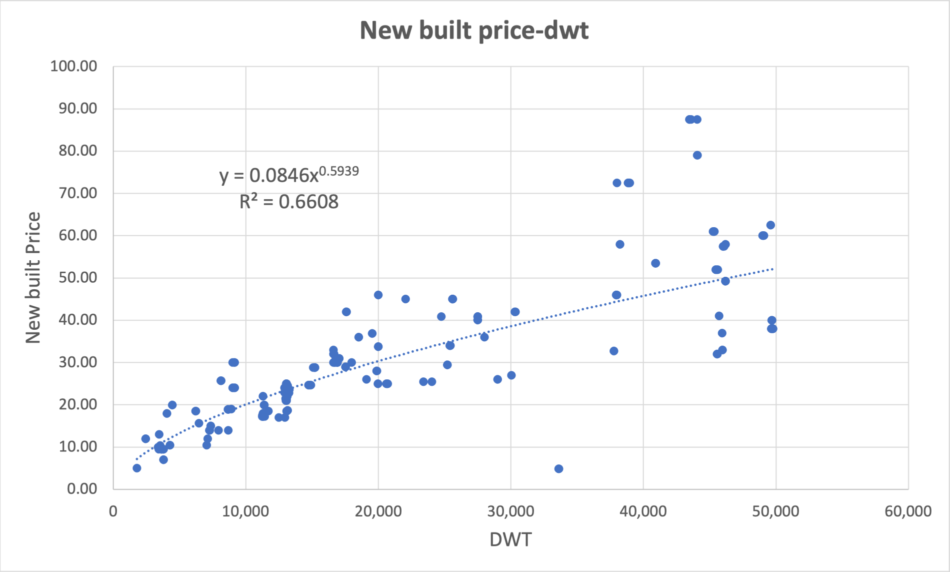


Figure 6.1: CAPEX of a chemical tanker. Data retrieved from Clarksons.

CAPEX engine

The capital costs for a diesel engine is set at 419.8[18] USD/kW and 639.5 USD/kW for dual engines as can be seen in table 6.1[14]. The operational cost of the engines is set at 2.5% of capital cost yearly[14].

Component	CAPEX{USD/kW]	OPEX [%]	Source
Diesel engine	419.8	2.5	[18]
Methanol dual fuel engine	639.5	2.5	[14]
Ammonia dual fuel engine	639.5	2.5	[14]
LNG dual fuel engine	639.5	2.5	[14]

Table 6.1: The capital costs of diesel and dual fuel engines

CAPEX of exhaust gas cleaning

The capital cost of a SCR system is assumed to be 46.51 USD/kW installed engine power[17]. The operational cost of an SCR is estimated at 6.98 USD/kWh[17].

Component	CAPEX{USD/kW engine power]	OPEX [USD/kWh]	Source
SCR	46.51	6.98	[17]

Table 6.2: The capital costs of diesel and dual fuel engines

Storage unit	CAPEX[eur/kWh]	CAPEX[USD/kg fuel]	Source
MGO	0.08	1.14	Baldi
HFO	0.10	1.29	Baldi
LNG	0.31	4.91	Baldi
Ammonia	0.15	0.90	Baldi
MeOH	0.14	0.90	Baldi

Table 6.3: The capital costs of storage[5]

CAPEX fuel storage

The cost of fuel storage are based on the weight of fuel stored and can be found in table 6.3. Operational costs of tanks are neglected.

6.0.4. Vessel operational and voyage costs

The operating costs for a vessel include:

- Crew costs CAPEX
- Maintenance: routine engineering, dry docking
- Fabric maintenance
- Insurance: hull, P&I,loss of hire, etc.
- Administration
- Regulatory costs
- Management fee

Earlier studies show that these operational costs can vary significantly between ship owners, this study assumes the operational costs to be 2.25% op the ship new-built costs annually[21][73]. This is built up from 1.00% non-crew operating cost and 1.25% crew cost.

Furthermore the operational cost of the SCR system are estimated at 6.98 USD/kWh.

6.0.5. Fuel cost

The fuel cost are calculated using formula 6.5

$$\text{Fuel Cost} = \sum_{y=1}^{years} \left(FC_{pilot,y} \cdot Pr_{pilot,y} + FC_{alter.,fossil,y} \cdot Pr_{alter,fossil,y} + FC_{alter.,renewable,y} \cdot Pr_{alter,renewable,y} \right) \tag{6.5}$$

where:

FC_{pilot} = fuel consumption of pilot fuel in year ’y’
$FC_{alter,fossil}$ = fuel consumption of the fossil version of the alternative fuel in year ’y’
$FC_{alter,renewable}$ = fuel consumption of the renewable version of the alternative fuel in year ’y’
Pr_{pilot} = fuel price of pilot fuel in year ’y’
$Pr_{alter,fossil}$ = fuel price of the fossil version of the alternative fuel in year ’y’
$Pr_{alter,renewable}$ = fuel price of the renewable version of the alternative fuel in year ’y’

6.0.6. Carbon tax

The total carbon tax is calculated using formula 6.6

$$\text{Carbon tax} = \sum_{y=1}^{years} \left(FC_{pilot,y} \cdot EF_{pilot} \cdot CT_y\right) \tag{6.6}$$

$$+ \sum_{y=1}^{years} \left(FC_{alter.,fossil,y} \cdot EF_{alter.,fossil} \cdot CT_y\right) \tag{6.7}$$

$$+ \sum_{y=1}^{years} \left(FC_{alter.,renewable,y} \cdot EF_{alter.,fossil} \cdot CT_y\right) \tag{6.8}$$

$$\tag{6.9}$$

where:

FC_{pilot} = fuel consumption of pilot fuel in year ’y’ in tons
$FC_{alter,fossil}$ = fuel consumption of the fossil version of the alternative fuel in year ’y’ in tons
$FC_{alter,renewable}$ = fuel consumption of the renewable version of the alternative fuel in year ’y’ in tons.
EF_i = The emission factor of the fuel in tonCO_2 equivalent per ton fuel as calculated in chapter 3
CT_y = The carbon tax in year per ton CO_2 eq.

7
Results: scenario 1 to 6

In this chapter, scenarios 1 to 6 will be analysed. In these scenarios, vessels operate at a 70% emission intensity reduction during their entire lifetime compared to the basecase. This is an emission reduction goal that is more ambitious than IMO goals but could be considered by vessel operators. To analyse in the cost of achieving this and to find the best alternative fuel for a broad range of vessels and operational profiles, a general analysis is first done in section 7.1. Next a more in detail case study is done in section 7.2.

7.1. General analysis

The goal of this section is to get an general insight into the most financially attractive alternative fuel for a broad range of vessels and operations. To achieve this goal, a broad range of vessels with different design speeds, capacities, trade distance were generated to be analysed. Then all six fuel price and carbon tax scenario's were applied to these vessels. Since this gives a large amount of combinations, some variables were restricted to several sizes. This gives the following combination of vessel variables:

- Capacity: 5000, 20000 and 45000 ton deadweight. This covers the smallest to the largest chemical tankers.
- Design speed: varied from 9 knots to 20 knots. This is a wide range around the standard speed of approximately 13.5 to 15 knots of a chemical tanker.
- Trade distance (round trip): 2000, 4000 and 12000 nm which cover almost all trade routes of chemical tankers[58].

To be able to analyse this broad range of vessels, these were first translated into figures. Two of these figures can be seen in figure of this can be seen in figure 7.1 and 7.2. A single figure gives the results for all three capacities, all speeds, one trade distance, one fuel scenario and one carbon tax scenario. This resulted in 18 figures as can be found in Appendix C for all combinations of carbon tax, fuel price and trade distance.

In almost all scenario's it was found that ammonia is positioned to be the most cost-effective solution for a vessel that operates at an emission intensity reduction of 70% during its entire lifetime. However doing so generally results in significant TCO increases as can be seen in the figures in appendix C.

Further analysing the figures, it can be seen that design speed is a key driver in the increase in cost. This can also be clearly seen in figure 7.1, where vessels operating at lower speeds around 12 knots experience a limited increase in TCO when operating compliant with the regulation. However for higher design speeds, it can be seen that the TCO of the compliant vessels increases significantly faster than cost of the non-compliant MGO vessel.

Influence of increase of displacement

One exception on ammonia being the most cost effective solution was found for small-scale vessels operating at relatively high speed on long distance trades. This can be seen in figure 7.2. For such vessels it found that

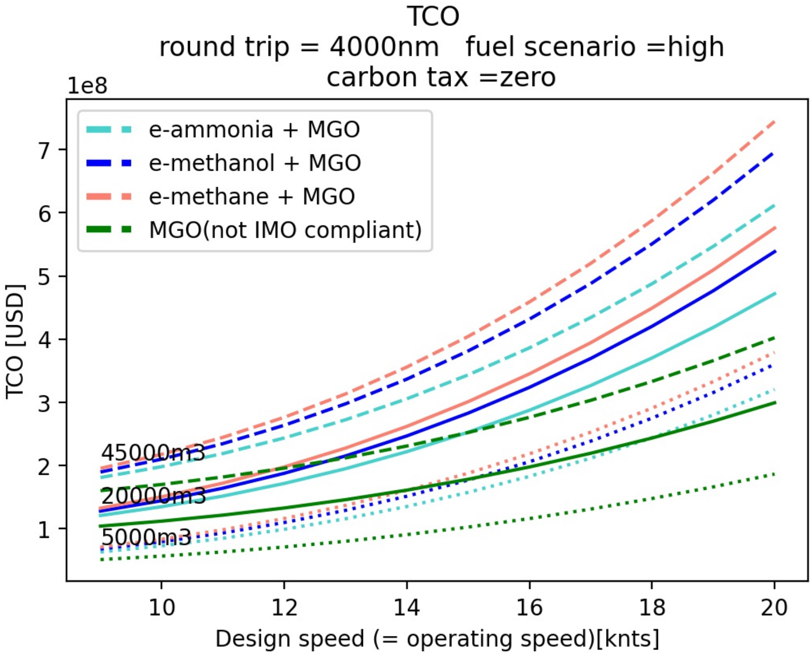


Figure 7.1: The TCO of vessels with a deadweight of 5000, 20000 and 45000 tons for various fuels under a 'high' fuel scenario and 'zero' carbon tax on a trade distance of 2000nm round trip. The green line depicts the cost reference line. This is a completely MGO powered vessel that does not comply with the emission intensity targets, but does pay carbon tax if the carbon tax scenario requires so.

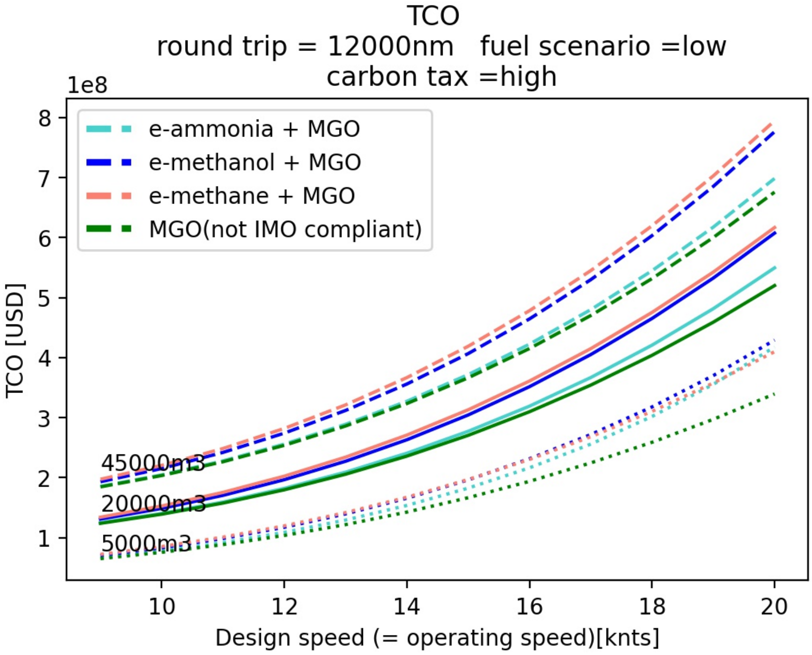


Figure 7.2: The TCO of vessels with a deadweight of 5000, 20000 and 45000 tons for various fuels under a 'low' fuel scenario and 'high' carbon tax. Trade distance is 12000nm round trip.

ammonia performs slightly worse than methane.

It was found that for these small vessels operating on long distance trades at high speed, there is a significant increase in displacement for methanol and especially ammonia. This is shown in figure 7.3 for a 5000 tons vessel operating at a trade of 12000nm. This figure shows the increase of displacement for various design

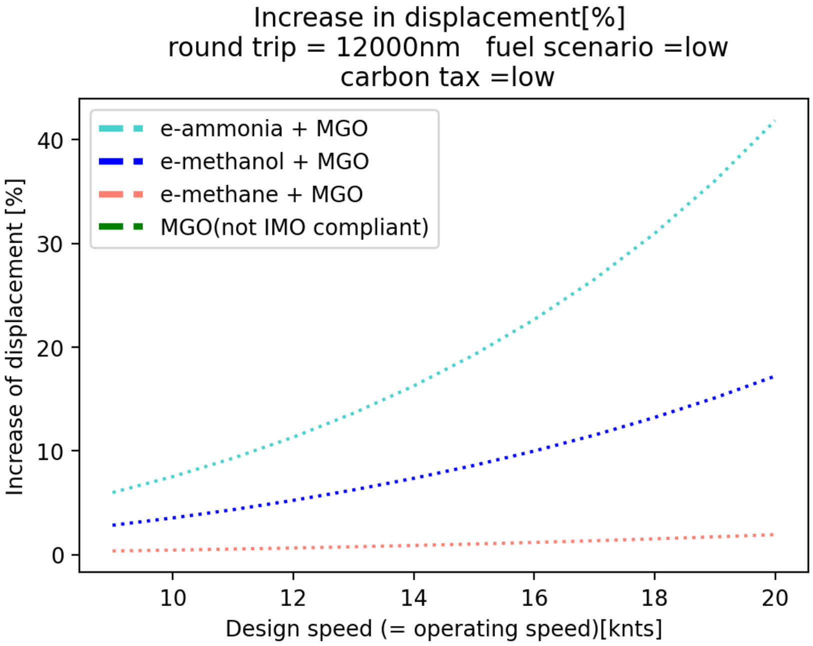


Figure 7.3: The increase in deadweight of a tanker with a deadweight of 5000 tons on a trade with 12000nm roundtrip. The carbon tax is 'low', the fuel scenario is 'low'. It can be seen that the use of ammonia as renewable fuel leads to a significant increase in deadweight.

speeds for the different fuels. There it can be seen that the displacement can increase up to 40% for ammonia. This significant increase in deadweight is a result from the lower energy density of the fuels and the weight of the required tanks. For higher speeds, the increase in displacement is so significant that the results should be interpreted with caution. This because the model uses the Admirality constant to estimate the installed power on a vessel with increased resistance. This method is well proven for small increases in displacement but might not be accurate for large increases in displacement as seen here[59]. For the mid and large scale vessels, the increase in displacement was found to be 10% at most.

Finally it should be noted that this exception has limited practical value since such vessels are (almost) non-existent considering that chemical tankers of such size generally operate on shorter trades and are built for lower design speeds.

7.2. Case analysis

The previous section gave an analysis of a broad range of vessels, operations and scenario's. To get better insight into the absolute financial consequences of operating with 70% less emission intensity three case studies will be analysed in this section. These cases are a small-scale, mid-scale and large-scale tanker which are further explained below. Cases are based on the top trade routes for chemical tankers[58].

- **Small-scale:** a tanker with a deadweight of 5000 tons that sails with a speed of 13.5 knots on a trade with a round trip distance of 2000nm. This can be a short trip within Europe[58].
- **Mid-scale:** a tanker with a deadweight of 20000 tons that sails with a speed of 15 knots on a trade with a round trip distance of 4000nm. This can be a trade between the north west Europe and the Mediterranean[58].
- **Large-scale:** a tanker with a deadweight of 45000 tons that sails with a speed of 15 knots on a trade with a roundtrip distance of 12000nm[58]. This can be a trade between the middle east and north east Asia[58].

For the cases above the increase in cost has been determined as can be seen in table 7.1. The increase in cost has been depicted as a relative increase compared to a non-complying vessel that operates on MGO but does pay carbon taxes.

As can be seen in table, it was found that ammonia is the most cost-effective alternative fuel to comply with the decarbonization requirements for all cases. In most cases, achieving the required emissions reduction goals results in a increase in cost compared to the reference case. Only for small and mid scale vessels, scenario 6 has a reduction in cost compared to the MGO reference case. In these cases it is not only required but also economically beneficial to comply with the decarbonization pathway.

Immediate 70% emission intensity reduction

Scale	**Carbon price**	**E-Fuel price**	**Scenario**	**100% MGO reference case [mln USD]**	**NH3 [% increase]**	**MeOH [% increase]**	**CH4 [% increase]**
Small scale	None	high	1	79.4	42.3	59.6	69.2
		low	2	79.4	28.1	44.1	47.4
	Low	high	3	92.8	26.3	41	49.3
		low	4	92.8	14.1	27.8	30.6
	High	high	5	112.1	10	22.2	29
		low	6	112.1	-0.1	11.2	13.6
Mid-scale	None	high	1	178.4	41.7	58.6	68.8
		low	2	178.4	27.7	43.3	47.2
	Low	high	3	208.3	25.9	40.4	49.1
		low	4	208.3	13.9	27.3	30.6
	High	high	5	251.2	9.8	21.8	29
		low	6	251.2	-0.2	10.9	13.7
Large-scale	None	high	1	265.8	41.1	55.3	65.6
		low	2	265.8	27.9	41	45.6
	Low	high	3	307.1	26.4	38.7	47.6
		low	4	307.1	14.9	26.3	30.3
	high	high	5	366.2	11.1	21.4	28.9
		low	6	366.2	1.4	11	14.3

Table 7.1: Overview of TCO for a small-,mid- and large-scale chemical tanker. For ammonia, methanol and methane the relative increase in cost is shows compared to a vessel that operates on 100% MGO but does pay a carbon tax.

7.3. Conclusion

The goal of this chapter was to analyse and get more insight into the TCO of chemical tankers that need to achieve a 70% emission intensity reduction during their entire lifetime. This emission reduction was achieved by mixing in a renewable alternative fuel with the MGO.

In almost all combinations of scenario's, trade distances and vessel sizes it was found that ammonia is positioned to be the most cost-effective solution. The only exception found was for for small scale vessels operating at high speeds and on long trade distances. In this case ammonia has similar cost as methanol and methane. It was found that the increase in displacement of these small scale tankers using ammonia is significant due to the weight of fuel and storage tanks. This increases the fuel consumption, which reduces the competitive position of ammonia.

8

Results: scenario 7 to 12

In this chapter the TCO of vessels complying with IMO emission intensity reduction on a yearly basis will be discussed, i.e. the vessel has to comply with increasingly strict regulation. In 2030 the vessel will have to operate with a 40% intensity reduction compared to the base case, slowly increasing to a intensity reduction of 70% in 2050. To analyse the influence of achieving this on the TCO and to find the best alternative fuel for a broad range of vessels and operational profiles, a general analysis is first done in section 8.1. Next a more in detail case study is done in section 8.2.

8.1. General analysis

Similar as in general analysis in chapter 7, the goal of this section to get better insight into the most financially attractive alternative fuel for a broad range of vessels and operations. To achieve this goal, a range of vessels with different design speeds, capacities and trade distance were generated to be analysed for the different scenarios. These variables were varied within the same ranges as in chapter 7. Then all six fuel price and carbon tax scenario's were applied to these vessels. This resulted in 18 figures as can be found in Appendix

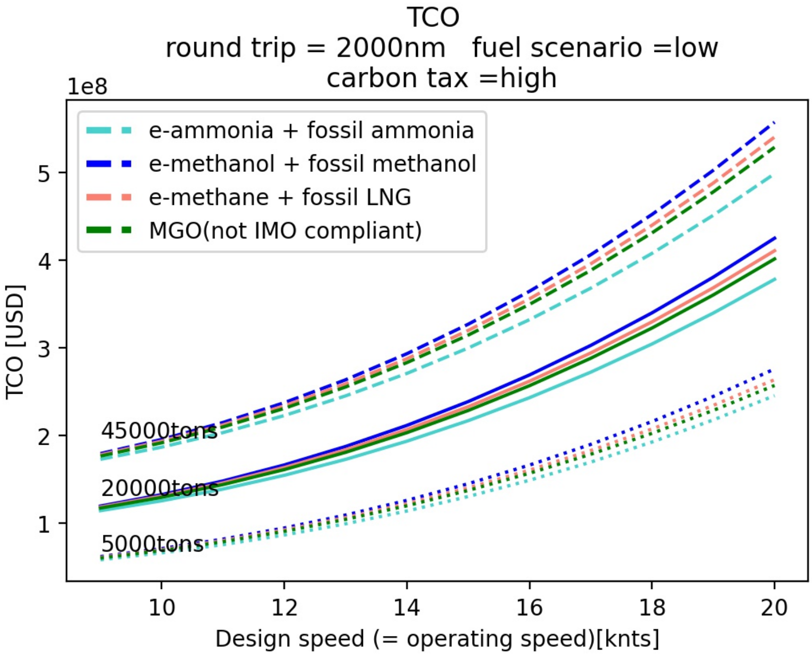


Figure 8.1: The TCO of vessels with a capacity of 25000, 90000 and 180000 for various fuels under a 'high' fuel scenario and 'zero' carbon tax on a trade distance of 1000miles round trip. The green line depicts the cost reference line. This is a completely MGO powered vessel that does not comply with the emission intensity targets, but does pay carbon tax if the carbon tax scenario requires so.

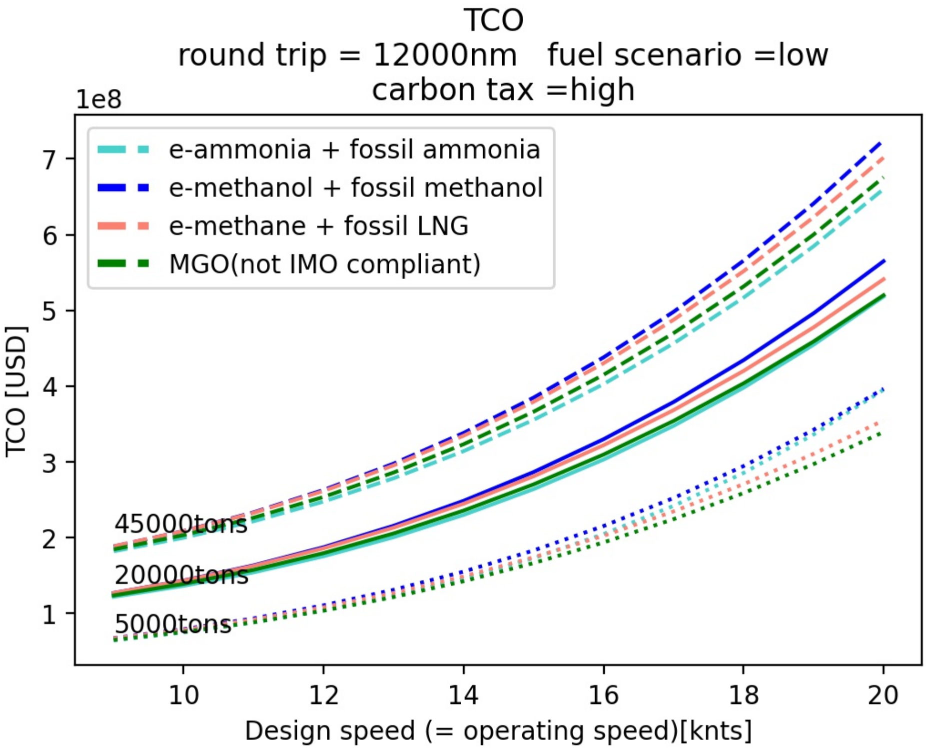


Figure 8.2: The TCO of vessels with a deadweight of 5000, 2000 and 45000 tons for various fuels under a 'high' fuel scenario and 'zero' carbon tax on a trade distance of 1000miles round trip. The green line depicts the cost reference line. This is a completely MGO powered vessel that does not comply with the emission intensity targets, but does pay carbon tax if the carbon tax scenario requires so.

D for all combinations of variables. One figure gives the results for all three capacities, all speeds, one trade distance, one fuel scenario and one carbon tax scenario. A example of the results is shown in figure 8.1 for a 2000nm trip for 'low' renewable fuel prices and a 'high' carbon tax. Figure 8.2 shows the results for a 12000nm trade with 'low' renewable fuel prices and a 'high' carbon tax.

Analysing all 18 generated figures, it was found that in almost all scenario's ammonia is positioned to be the most cost-effective solution for a vessel that complies with IMO goals on a year by year bases.

Sensitivity to design speed, vessel size and trade distance

Limited influence of design speed, vessel size or trade distance on this ammonia being the most cost effective solution was found. The only exception to this is found for fast small scale vessels on the trade of 12000nm. In that case methane performs better independent of the fuel price and carbon tax scenario. In chapter 7 the same exception was found.

Sensitivity to carbon tax

It was found that applying a carbon tax has large influence on the relative cost of IMO compliant vessels compared to a MGO fuelled non-IMO compliant reference vessel. It was found that when no carbon-tax was applied, the relative cost of a compliant vessel is significantly larger than a non-compliant-MGO vessel. This can be concluded from figure D.2 and figure D.14, for which all variables are the same except a different carbon tax. When a high carbon tax is applied this greatly reduces the relative cost. This is a logical result since a carbon tax will have a smaller impact on vessels with less emissions. However no influence was found on the relative competitive position of ammonia, which is the most cost-effective alternative fuel independent from the carbon tax.

Sensitivity to price scenario

It was found that a low renewable fuel price scenario reduces the relative increase in TCO of a compliant vessels compared to a 'high' renewable fuel price scenario, as can be expected. This because the fuel cost of the compliant vessel are reduced in such a scenario. No influence of the fuel price was found on ammonia being the fuel with the lowest TCO. It was found that in the 'high' fuel price scenario, the TCO of a methane fuelled vessel increases relatively much. This makes methane generally as expensive as methanol, while for a 'low' renewable fuel price scenario, the TCO of a methane powered vessel is generally lower.

8.2. Case analysis

Next a more specific analysis is done for three case studies, being a small-scale, mid-scale and large-scale tanker that were selected in chapter 7. The results of the three cases for all six scenario's can be found in table 8.1. It can be seen that ammonia as alternative fuel results in the smallest increase in cost for all scenarios and all vessel sizes. This would therefore be the most attractive alternative fuel when assessed from a solely economically perspective.

IMO emission goals compliant on yearly basis

Scale	**Carbon price**	**E-Fuel price**	**Scenario**	**100% MGO reference case [mln USD]**	**NH3 [% increase]**	**MeOH [% increase]**	**CH4 [% increase]**
Small scale	None	high	7	79.4	27.9	41.9	41.5
		low	8	79.4	17.2	30.3	25
	Low	high	9	92.8	16.4	28	27.5
		low	10	92.8	6.8	18	13.5
	High	high	11	112.1	4.2	13.9	13.7
		low	12	112.1	-4.9	4.9	2
Mid-scale	None	high	7	178.4	27.5	41.1	41.3
		low	8	178.4	16.9	29.7	25.1
	Low	high	9	208.3	16.2	27.5	27.5
		low	10	208.3	6.7	17.6	13.6
	High	high	11	251.2	4.1	13.6	13.8
		low	12	251.2	-4.9	4.7	2.2
Large-scale	None	high	7	265.8	28.1	39.1	40.3
		low	8	265.8	18	28.4	25.3
	Low	high	9	307.1	17.4	26.5	27.5
		low	10	307.1	8.3	17.3	14.5
	high	high	11	366.2	5.8	13.6	14.6
		low	12	366.2	-2.9	5.1	3.6

Table 8.1: The results for the three case studies. The small scale vessel has a deadweight of 5000 tons and operates at 13.5 knts on a trade of 2000nm round trip. The mid scale has a deadweight of 20000 tons and operates at a speed of 15 knots on a trade of 4000nm round trip. Finally the large scale vessel has a deadweight of 45000 tons and operates at a speed of 15 knots on a trad eof 12000nm round trip.

8.2.1. Break-even year for scenario 12

As can be seen in table 8.1 there are three solutions (scenario 12 for all sizes) in which the ammonia fuelled solution does not only comply with the decarbonization strategy, but also has a lower TCO than the MGO reference case. For these cases, the timeline of the total cost of ownership was analysed to find the breakeven point between MGO and ammonia. Note that the yearly amortisation is included in the curve as a yearly payment, not as a single payment at the start of the lifetime of the vessel. For the mid scale vessel this is depicted in figure 8.3. For the small and large scale vessel, the timelines can be found in appendix D. As can be seen in the figure, the breakeven point of ammonia lies around 2044. For the other fuels, the breakeven points lie outside the lifetime of the vessel. It can be seen that both methanol and methane depict a slowing curve, while the reference case shows an increasing curve. For a vessel with a longer lifetime, a breakeven point can therefore be expected. The small scale vessels has its breakeven points for ammonia around 2044, the large scale around 2046.

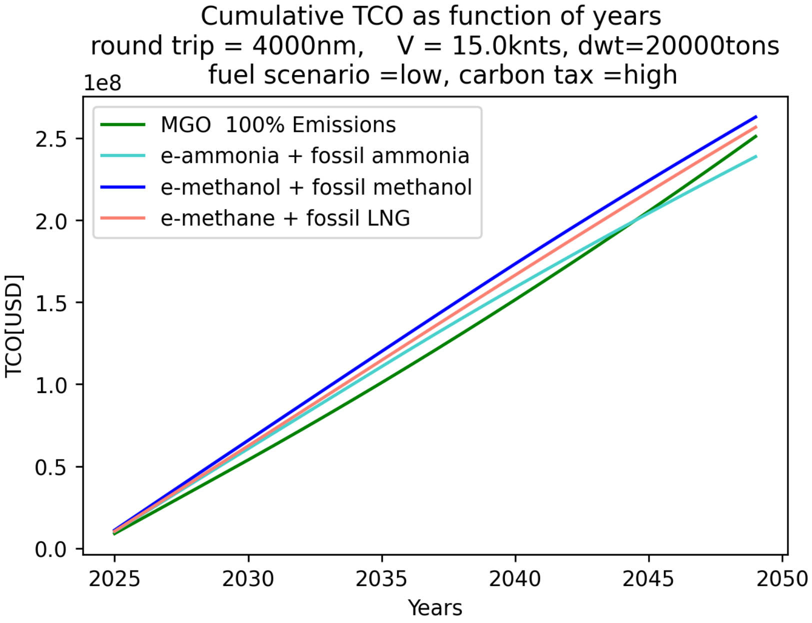


Figure 8.3: The cumulative TCO for the midscale vessel in scenario 12. The yearly amortisation of the loan is integrated in the yearly cost.

8.3. Conclusion

The goal of this chapter was to get more insight in different factors which can influence TCO of chemical tankers for scenario 7 to 12. In these scenarios, the vessel is required to comply stricter emission regulation on a yearly bases. This emission reduction was achieved by making a complete switch to a combination of the fossil and renewable version of an alternative fuel.

Similar as in chapter 7 it was found that for almost all scenario's, trade distances and vessel sizes, ammonia is positioned to be the most cost-effective solution. This conclusion showed limited sensitivity to the height of the carbon tax, design speed, vessel size or fuel price. The competitive position of ammonia was found to be sensitive to the trade distance for small-scale vessels. For small-scale vessels operating at long distances(12000nm roundtrip) at relative high speeds, it is was found that methane has the lowest TCO.

9

Results: scenario 13 to 18

In this chapter the financial impact of using speed reduction and alternative fuels to comply with IMO emission goals is analysed. As in the previous chapter, the decarbonization pathway is the ’following yearly IMO goals’ pathway as discussed in the scenario’s in chapter 2. So in 2030 the vessel will operate with 40% intensity reduction compared to the base case, and each year the vessel will need to comply with stricter regulation.

To achieve this goal a model was developed that was explained in chapter 5 called the "model for scenario 13 to 18". This model will give a TCO of a vessel, which is not sufficient to analyse the financial impact of both speed reductions and alternative fuels. This because the revenue of a vessel will also decrease if the speed of the vessel is decreased. Therefore the profit of the vessel will be used as an indicator in this chapter. To calculate the profit of a vessel, first the revenue is calculated using formula 9.1. The number of port calls is calculated with the assumption that a vessel spends 24 hours in an harbour.

$$\text{Revenue}_{\text{Annual}} = \text{Freight Rate} \cdot \text{Port calls} \cdot \text{M}_{cargo} \tag{9.1}$$

Where:

Freight Rate = revenue to transport 1 ton of product on a specific trade in USD/ton
Port calls = number of times that cargo is delivered in one year
M_{cargo} = the mass of cargo transported on a trade

Next the revenue and the TCO can be used to calculate the overall profit of the vessel using equation 9.2:

$$\text{Profit} = \text{Revenue} - \text{TCO} \tag{9.2}$$

9.1. Cases and freight rates

In the previous chapters 7 and 8, three cases were analysed being a small, mid and large scale. In this chapter only one large scale case will be analysed, but the freight rate is introduced as a new variable. It is chosen to only analyse one ship size to limit the amount of combinations of variables.

- **Large-scale:** a tanker with a deadweight of 45000 tons including bunkers. The vessel sails originally with a (reference) speed of 15 knots on a trade with a round trip distance of 12000nm. This is the distance between the Rotterdam and Mumbai.

It is assumed that the density of the cargo is 0.7 ton/m3, which is a average density for oil products. Furthermore it is assumed that the freight rate to transport 1 ton of product from Rotterdam to Mumbai is $85 for a ’high’ freight rate scenario. This was the rate in January 2020[24]. To analyse the sensitivity of the results to freight rate, a ’low’ freight rate scenario will also be reviewed. For this ’low’ freight rate scenario, the rate is reduced to $45. While the ’base case’ speed is 15 knots, the operational speed of the vessel will be varied between 4 and 20 knots. This operational speed is kept constant over the lifetime of a vessel, to limit the complexity of the problem. In real life a vessel could further optimise its operations by also varying the operational speed during its lifetime depending on fuel prices and other circumstances.

9.2. Results

The results for all fuels, fuel price scenario's and carbon tax scenario's can be found for both freight rates in Appendix E. An example of these results is shown in figure 9.1 for a 'low' freight rate, 'high' fuel, and 'high' carbon tax scenario. For this scenario, it can be seen that methane is the optimal fuel choice with an optimal operational speed of 11 knots. However it can be seen that both methanol and ammonia only perform slightly worse.

For the high freight rate, an example of these results is shown in figure 9.2 for a 'low' fuel, and 'high' carbon tax scenario. For this scenario, ammonia is the optimal fuel choice with an optimal operational speed of 14.5 knots. Furthermore the difference with methane and methanol is much larger.

To give an overview of the results, the fuel with the highest profit and affiliated optimal operational speed is shown in table 9.1.

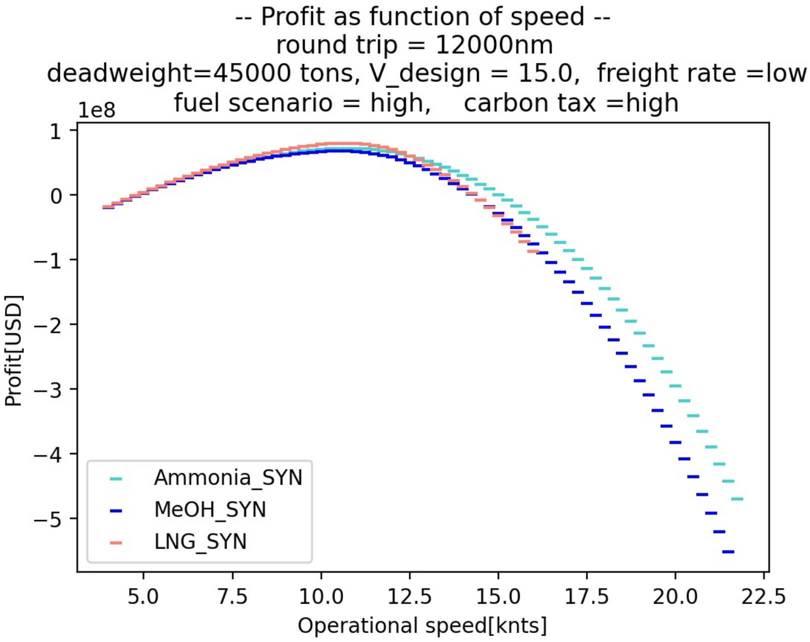


Figure 9.1: Profit analysis for a large scale tanker operating between the Rotterdam and Mumbai. This analysis is done for a 'low' freight rate, 'low' fuel, and 'high' carbon tax scenario. The reference speed is 15 knots, this is the speed at which the 2008 base case is set for the determination of IMO emission reduction goals. Operational speed can be seen on the lower axis, profit on the vertical axis. The fuels in the figure are Ammonia, Methanol and LNG(methane).

9.3. Analysis of results

Analysing the results in table 9.1 several things can be noted about the sensitivity to changes of variables:

Sensitivity of results to the carbon and fuel price scenario

Limited influence of the carbon tax and fuel scenario was found on the outcome of the most optimal fuel. The optimal operational speed however shows large correlation with the carbon price and fuel prices. For both both a higher carbon tax and high renewable fuel price scenario, the operational speed decreased. Resistance increases with a third power, while revenue is correlated linearly with speed. Therefore a higher fuel price will decrease the optimal speed.

Sensitivity of result to the freight rate

First of all it can be seen that the optimal operational speed of the vessel is highly dependant on the freight rate. When the freight rate is 'high', the vessel operates on a higher optimal speed than during a 'low' freight

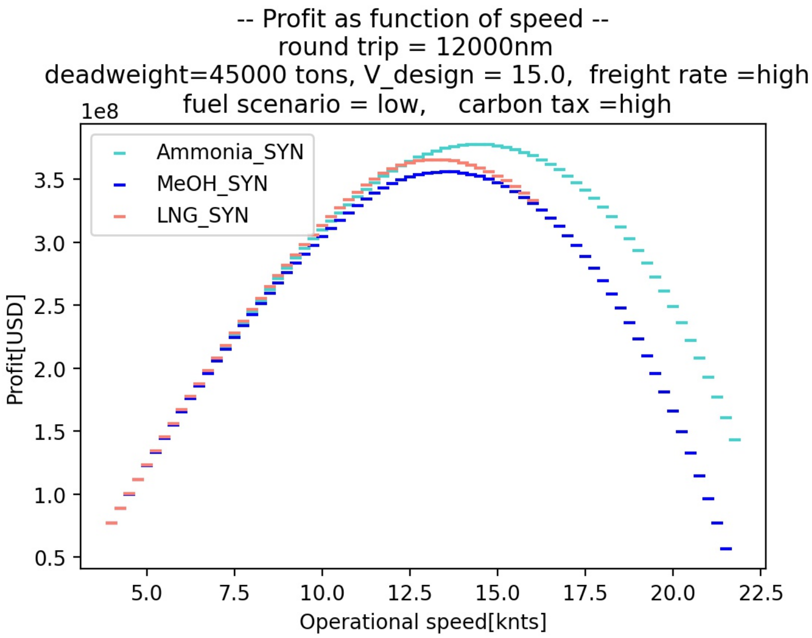


Figure 9.2: Profit analysis for a large scale tanker operating between the Rotterdam and Mumbai. This analysis is done for a 'high' freight rate, 'low' fuel, and 'high' carbon tax scenario. The reference speed is 15 knots, this is the speed at which the 2008 base case is set for the determination of IMO emission reduction goals. Operational speed can be seen on the lower axis, profit on the vertical axis. The fuels in the figure are Ammonia, Methanol and LNG(methane).

Profit for various scenario's

Scale	**Freight Rate**	**Carbon price**	**E-fuel Price**	**Scenario Nr.**	**Fuel with highest profit**	**Optimal operational speed [knts]**
Large-scale	Low	None	High	L13	Methane	11.25
			Low	L14	Methane	11.5
		Low	High	L15	Methane	11
			Low	L16	Methane	11.5
		High	High	L17	Methane	10.75
			Low	L18	Methane	11
	High	None	High	H13	Ammonia	14.0
			Low	H14	Ammonia	15.0
		Low	High	H15	Ammonia	13.75
			Low	H16	Ammonia	14.75
		High	High	H17	Ammonia	13.5
			Low	H18	Ammonia	14.5

Table 9.1: Results of profit analysis for a 45000 ton chemical tanker at a high freight rate of $85 and low freight rate of $45 for a trade between Rotterdam am Mumbai.

rate scenario. This is a logical result, since the additional fuel cost can be compensated by the higher revenue up to certain point.

Secondly the optimal fuel choice showed significant sensitivity to the freight rate. It can be seen that methane results in the highest profit in all scenarios with a low freight rate. Meanwhile, it can be seen that ammonia results in the highest profit in all scenario's with a high freight rate. The profit as seen in the table is a complex gathering of influences such as CAPEX, OPEX, fuel cost, freight rates, carbon taxes and operational speeds. However the dominance of methane in the low freight rate scenarios, can partially can be explained by look-

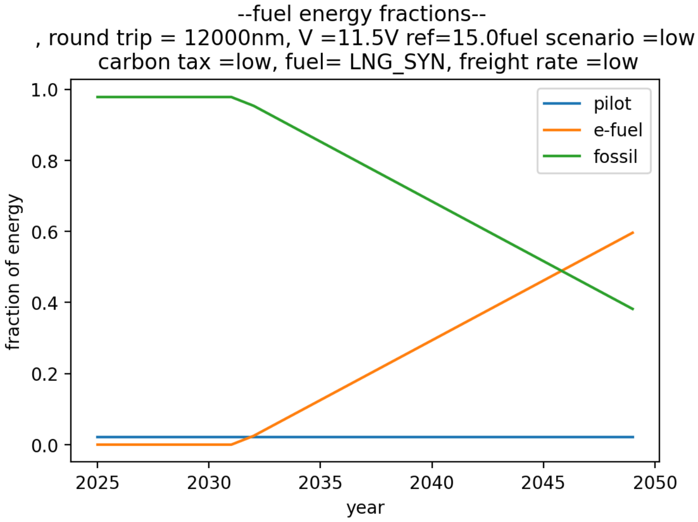


Figure 9.3: The energy fraction of the fuels on board of a methane powered large scale tanker. The fuel scenario is ’low’, the carbon tax is ’low’, the freight rate is ’low’. The green line depicts how much of the energy used for propulsion comes from fossil methane. The orange line depicts how much from the energy comes from e-methane. The blue lines shows the fraction of energy that is generated by the pilot fuel(MGO). This show for each year. As can be seen, there is no change over the years and the vessel operates on fossil methane and pilot fuel, i.e. no renewable fuel is used.

ing at the combination of renewable and fossil fuels as used in the scenarios.

It can be seen in table 9.1 that the optimal speed for the low freight rate scenarios is significantly lower than the reference speed of 15 knots. Lowering the speed of the vessel will not only reduce fuel cost but also reduces the emission intensity of the vessel. Due to this reduction in emission intensity achieved by the speed reduction, the need to use renewable fuels to lower emissions is also reduced. Therefore the vessel can now operate using relatively much fossil fuel. This can seen by comparing the ratio of fossil and renewable fuels of scenario L16 and H16. Figure 9.3 show the annual combination of pilot, fossil and renewable fuel for the methane powered vessel for scenario L16. It can be seen that the vessel operates completely on fossil fuel up to 2032, after which more renewable methane is gradually used. When looking at the summation of fuel prices and carbon taxes affiliated to the emissions of the respected fossil fuels it was found earlier that fossil methane remains a relatively affordable fossil fuel. This can also be seen in appendix A, for all combinations of fuel prices and carbon taxes. Hence, when the optimal operational speed is low due to a relatively low freight rate, the position of methane as fuel will improve relatively. This is only one of the factors influencing the profit, with many more such as capital cost also influencing the result. However in this specific case, methane is also the most affordable fuel.

Figure 9.4 show the annual combination of pilot, fossil and renewable fuel for the ammonia fuelled vessel of scenario H16. It can be seen that the vessel uses a significant amount of renewable fuel compared to scenario L16. This is required due the optimal speed of 14.75 knots, which is higher than the optimal speed found for scenario L16. This increase in speed is a result of the higher freight rate. Since this speed is only marginally lower than the reference speed, significant use of renewable fuel is required to comply with the decarbonization pathway. As was seen in chapter 8, the use of renewable fuel is relative expensive for a methane powered vessel due to the high price of renewable methane. Meanwhile renewable ammonia is more affordable compared on a energy base, therefore the competitive position of ammonia will therefore improve in the high freight rate scenario. In this specific case, ammonia is also the most profitable.

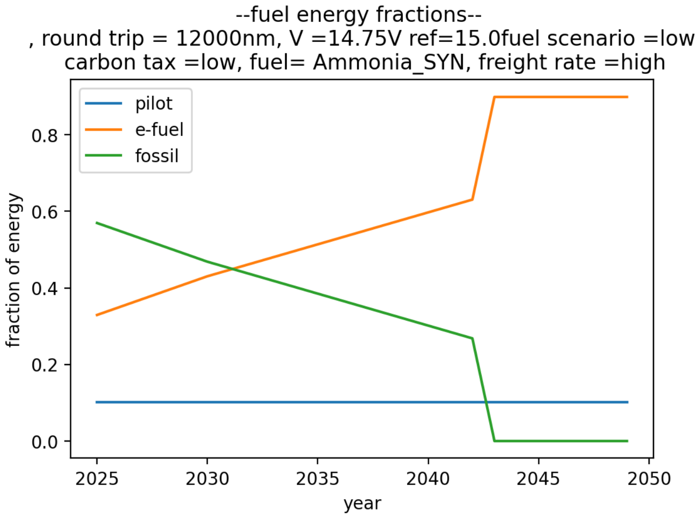


Figure 9.4: The energy fraction of the fuels on board of a methane powered large scale tanker. The green line depicts how much of the energy used for propulsion comes from fossil methane. The orange line depicts how much from the energy comes from e-methane. The blue lines shows the fraction of energy that is generated by the pilot fuel(MGO). This show for each year. As can be seen, the use of fossil methane decreases and the use of renewable methane increases. This change is caused by the increasingly stricter IMO regulation. It should be noted that the carbon tax is not the factor pushing the use of renewable methane. If a carbon tax would have increased the cost of fossil methane enough to make e-methane competitive, then a complete switch to renewable methane would be present.

9.3.1. Sensitivity to methane slip

The model up to now assumed a methane slip of 0.02 grams for each gram of methane/LNG burned. As can be seen in chapter 3, methane slip is in that case responsible for 13% of the CO_2 equivalent emission when of the life cycle emissions of fossil LNG. For renewable methane the methane slip is responsible for 56% of the life cycle emissions. Methane slip is therefore a important factor to be considered. MAN engines stated they expect that the methane slip can be limited to 0.2 g/kWh of engine power[60]. This is equal to 0.00136 g/g fuel assuming a 50% engine efficiency. This would reduce the well-to-wake emission from methane from 87.61 gr CO_2 eq/MJ fuel to 76.96 CO_2 eq/MJ, i.e. a reduction of 12.1%. For renewable methane, the well-to-wake emissions are reduced from 20.33 CO_2 eq/MJ to 9.68 CO_2 eq/MJ. This could influence the outcome of the model, and therefore the case study is performed again taking into account the lower methane slip. The results can be found in table 9.2.

Comparing the results in this table to the results in table 9.1 it can be seen that the optimal fuel for the low freight rate is still methane. However the optimal speed of the low freight rate has increased. This is a logical result of two influences:

- Firstly the lower well-to-wake emission reduce the carbon tax on both the renewable and fossil version of methane, hence the total cost of both fossil and renewable methane is lowered. With a lower fuel price, the competitive position of methane improves.
- Secondly the lower WTW emissions of fossil LNG reduces the required amount of renewable methane to comply with the decarbonization pathway. Since fossil LNG(including carbon tax) is significantly less expensive then renewable methane, this reduces the fuel cost of a methane powered vessel. This results in an improvement of competitive position of methane compared to ammonia and methanol.

Furthermore it can be seen that methane is now the optimal fuel for the 'high' fuel price scenarios(H13 to H18). This is the result of the same processes as discussed above.

Profit for various scenario's

Scale	Freight Rate	Carbon price	E-fuel Price	Scenario Nr.	Fuel with highest profit	Optimal operational speed [knts]
Large-scale	Low	None	High	L13	Methane	11.75
			Low	L14	Methane	12.25
		Low	High	L15	Methane	11.5
			Low	L16	Methane	12
		High	High	L17	Methane	11.25
			Low	L18	Methane	11.5
	High	None	High	H13	Methane	13.25
			Low	H14	Methane	14.25
		Low	High	H15	Methane	13.25
			Low	H16	Methane	14
		High	High	H17	Methane	13
			Low	H18	Methane	13.75

Table 9.2

9.4. Conclusion

The goal of this chapter was to analyse scenario 13 to 18 for a large scale chemical tanker. In these scenario's both alternative fuels and speeds reductions were used as means reduce the carbon intensity of the vessel. It was found methane is the optimal fuel choice for a large-scale chemical tanker when the freight rate is relatively low. This is mainly the result of fossil methane being a very affordable fuel compared to the fossil and renewable versions of methanol and ammonia. Furthermore it was found that the operational speed is reduced greatly in all scenario's to obtain the highest profit. For higher freight rates, it was found that ammonia is the most cost-effective fuel. Finally the influence of methane slip was assessed. It was found that the result were significantly sensitive to this change. With the lower methane slip, the position of methane improved significantly.

10

Conclusion

In this chapter, the conclusions of this study are explained and discussed. First a discussion of the results is presented. Afterwards the conclusion will first give an answer to sub research questions, and afterwards to the main research question. This is followed by recommendations for future work.

10.1. Discussion

In this section, the results of the research are discussed. This study is used to get insight into the financial impact of complying with different decarbonization pathways under various carbon taxes. The results of this study will give an indication of this impact, however the model is based on other literature and assumptions which have influence on the these results. While using this model for further research, it is important to use up to date data, improving the reliability of the model. Below the study will be further discussed in three parts: the scope, the model and scenarios and finally the ship design.

Based on the scope of the model:

- The prices of the renewable fuels are based on assumptions for the electricity price, electrolyser cost, capital cost and production cost prices. Meanwhile literature showed that the future development of these prices is highly uncertain. No sensitivity study was included to analyse the influence of changes in these parameters, reducing the reliability of these prices.
- Methanol and methane are carbon based fuels and the price of these synthetic fuels is therefore dependant in the cost of CO2. This study has looked at direct air capture as CO_2 source, however this is a relative expensive process compared to other CO2 sources such as capture from a point source at a factory. Since ammonia is not carbon based, the choice to only include DAC therefore improves the competitive position of ammonia in this study.
- This study only included wind power as renewable energy source. Other renewable energy sources such as hydro or solar can also be used in reality. These renewable energy sources can have different energy prices and different carbon intensities influencing the expected fuel price.
- No internal rate of return(IRR) was assumed for the electricity production and the fuel production. The inclusion of a IRR would increase would increase the cot for both, which could influence the outcome of the model.
- This study assumed that no distribution and bunker cost were present for the renewable fuels. In reality there are significant differences in bunker cost between fuels. Therefore bunker cost should be included for more reliably results.

Based on the model and scenarios:

- The results of the model can be used to get an impression of the financial impact of complying with decarbonization strategies.

- It was chosen to limit the combinations of decarbonization strategies and decarbonization pathways to three combinations. Mixing in of e-fuel with MGO has for example not been analysed for the gradual emission decarbonization pathway, while such a strategy could prove to be more cost-effective. Results should therefore only be interpreted as representative for the specific combination of decarbonization pathway and decarbonization strategy.
- The model assumes a fixed duration of time in the harbour for manoeuvring, discharging and loading independent of the vessel size. In reality the time needed for this can differ depending on the vessel size. Furthermore it was assumed that the vessel only consumes fuel while in transit, neglecting fuel consumption for operations in the harbour. The fuel consumption of these operations could influence the outcome of the model.
- It was found that a vessel can comply with decarbonization pathways while using a limited amount of renewable fuel if the speed of the vessel is reduced. This makes the outcome if the model potentially sensitive to relative and absolute price changes of fossil fuels. The model does not take this into account and assumes a fixed price for fossil fuels. In reality the absolute and relative prices of fossil fuels also show a high volatility, hence the results should be interpreted with this in mind.
- It was found that if the vessel uses both speed reductions and alternative fuel to comply with decarbonization strategies, the most cost-effective fuel is highly dependent on the freight rate. Methane is optimal for low freight rates, ammonia for high rates. The model only took the possibility of a constant speed reduction over the entire lifetime of the vessel into account. In reality the vessel could reduce its operational speed further during its lifetime which could lead to different results.

Based on the ship design:

- This study assumed that ammonia and LNG can be stored on deck. However this study showed thatthe weight of the fuel and storage tanks can be significant for alternative fuels. This could then marginalises the stability of a vessel. Furthermore it was assumed that there was no limit to the amount of volume the fuel tanks could occupy on deck, while there could be practical limitations to this.
- This study used the admiralty constant to adjust for the increased resistance due to additional fuel and fuel system weight. For some vessels it was found that the displacement can increase significantly, for these cases the accuracy of this method could be inadequate.
- This study assumed that vessels will use internal combustion engines as power source. However in the future fuel cells could be used on vessels. Fuel cells have the advantage that these do not have NO_x or CH4, emissions, while these emissions can be a problem for ICEs and increase the carbon tax paid by a vessel.
- This study assumed that LNG, ammonia and methanol have a thermal efficiency of 50%. Meanwhile literature showed that there can be differences between the fuels[4]. This could influence the relative competitive position of the fuels.
- The OPEX of the vessels in this model is determined based on two factors. The first is a fixed amount based on the CAPEX, the second part is based on the use of urea for the SCR unit. In reality differences between the fuels can be expected due to the large differences in chemical properties of the fuels.

10.2. Conclusion

Main research question of this study is: *What is the financial impact of using alternative fuels and speed reductions on a chemical tanker to comply with decarbonization regulation, considering various carbon tax scenario's?* First, the sub research questions are answered before the main research question is answered.

Sub-questions

1. *What are the life cycle emissions of the selected fossil and renewable fuels?*

   It was found that the life cycle emission of fossil MGO are 87.86 gr $CO_2\ eq/MJ$. Those of fossil ammonia are 97.63 gr CO_2 eq/MJ, those of e-ammonia re 7.76 gr CO_2 eq/MJ, those of fossil methanol are

89.38 gr CO_2 eq/MJ, those of renewable methanol are 8.55 gr CO_2 eq/MJ, those of fossil LNG are 87.6 gr CO_2 eq/MJ and those of e-methane are 20.33 gr CO_2 eq/MJ.

2. *What renewable fuel prices can be expected between 2025 and 2050 for renewable fuels depending on renewable electricity price scenario's and carbon tax scenario's ? And how do they compare to each other and to fossil fuels?*

   It was found that on a USD/GJ bases, renewable ammonia is expected to be the most cost effective e-fuel to produce between 2025 and 2050. Meanwhile methane and methanol are expected to have higher production cost. Furthermore it was found that renewable fuel prices can be expected to decrease as much as 50% for an 'high' renewable energy scenario and up to 60% for a 'low' renewable energy scenario between 2020 and 2050. This is a result of expected improvements in production efficiencies, decreasing capital cost and decreasing renewable power prices.

   Furthermore it was found that a carbon tax can improve the position of renewable fuels significant. With 'low' renewable fuel prices and a high carbon tax, ammonia could already become economically competitive as early as 2030.

3. *What is the financial impact of mixing in a minimal amount of renewable fuel with MGO on a vessel to achieve a 70% emission intensity reduction during its entire lifetime? And can trends be found in which alternative fuel is optimal depending on multiple variables?*

   In almost all combinations of scenario's, trade distances, vessel speeds and vessel sizes it was found that ammonia is positioned to be the most cost-effective alternative fuel to comply with the decarbonization pathway. The only exception found was for for small scale vessels operating at high speeds and on long trade distances. In this case ammonia has similar cost as methanol and methane. It was found that the increase in displacement of these small scale tankers using ammonia is significant due to the weight of fuel and storage tanks. This increases the fuel consumption, which reduces the competitive position of ammonia. In almost all scenarios a significant increase of TCO was found compared to the base case.

4. *What is the financial impact of using renewable and fossil alternative fuels on a vessel to comply with the IMO emission intensity goals? And can trends be found in which alternative fuel is optimal depending on multiple variables?*

   It was found that for almost all scenario's, ammonia is positioned to be the most cost-effective alternative fuel to comply with the decarbonization pathway. This conclusion showed limited sensitivity to the height of the carbon tax, design speed, vessel size, trade distance, design speed or renewable fuel prices. The competitive position of ammonia was found to be sensitive to the trade distance for small-scale vessels. For small-scale vessels operating at long distances(12000nm roundtrip) at relative high speeds, it is was found that methane has the lowest TCO. Furthermore in almost all scenarios a significant increase of TCO was found compared to the base case.

5. *What is the financial impact of using speed reductions, renewable alternative fuel and fossil alternative fuels on a vessel to comply with the IMO emission intensity goals? And can trends be found in which alternative fuel is optimal depending on multiple variables?*

   When both alternative fuels and speeds reductions were are used as means reduce the carbon intensity of the vessel, it was found methane is the optimal fuel choice for a large-scale chemical tanker when the freight rate is relatively low. For higher freight rates, it was found that ammonia is the most cost-effective fuel. Furthermore it was found that the operational speed is reduced greatly in all scenario's to obtain the highest profit. Finally the influence of methane slip was assessed. It was found that the result were significantly sensitive to this change. With the lower methane slip, the position of methane improved significantly.

Furthermore the model showed that methanol as fuel requires a lower capital cost than an ammonia LNG, but has relatively high fuel cost. Therefore it was expected that methanol could be the optimal fuel choice for vessels with a low fuel consumption. This trade off was not observed for the vessel sizes, trade distances and speeds analysed in this study.

To finalise it can be concluded that there is significant financial impact when a vessel is required to comply with the reviewed regulation. The cost of shipping increased in all analysed scenarios when measured in absolute cost. Only in extreme cases with high carbon taxes and low renewable fuel prices, it was found that decarbonization does not result in an increase in cost relative to the MGO reference vessel. This because the high carbon tax increases the TCO of the MGO fuelled vessels significantly in such cases. Furthermore it can be concluded ammonia is positioned to be the most cost-effective solution in almost all scenario's and vessels if only alternative fuels are used as decarbonization measure. If slow steaming is also used as a secondary emission mitigating measure, in combination with the use of alternative fuels, the most cost effective solution was highly dependent on the freight rate. For low freight rates methane was found to be financially optimal, for high freight rates it was found that ammonia is positioned as the best alternative fuel.

10.3. Future work

In this section, recommendations for future work are presented:

- The model has been used to analyse chemical tankers, but is well suited to be adjusted to analyse other vessel types. This could be done in further work.
- Methanol requires a lower capital than an ammonia or LNG fuelled vessel, but has higher operational cost. Therefore it can be expected that methanol is a good fuel choice for vessels with a low fuel consumption. The vessels analysed by this study did not show such a trade off, but further research could analyse smaller vessels where this trade off might be present.
- It was chosen to limit the analysed fuels to methanol, ammonia and methane. E-diesel was not included due to the expected high price. The results found that when the operational speed of the vessel is reduced, a vessel can comply with regulation using a limited amount of renewable fuel. Therefore e-diesel might prove to be a feasible solution as drop in fuel. While the production price might be higher, e-diesel avoids the higher capital cost of other renewable fuels.
- The study included a range of combinations of carbon taxes and decarbonization pathways. However reality, future scenarios are unknown. To be able to really make substantiated business choices, future research could be done into the probability of possible regulation.
- In this study a limited the amount of scenarios were included and paired with decarbonization strategies. In further work a more detailed view of the impact of regulations can be achieved by using a a Monte Carlo Simulation. Using such simulations, more possible regulations and decarbonization strategies can be combined and analysed.
- This model assumed that CO_2,CH_4 and N_2O are taken into account as greenhouse gas. However it is possible that future regulation will focus solely on carbon emissions. This study could be repeated while looking solely at carbon emissions.

A

Overview of integrated fuel cost per scenario

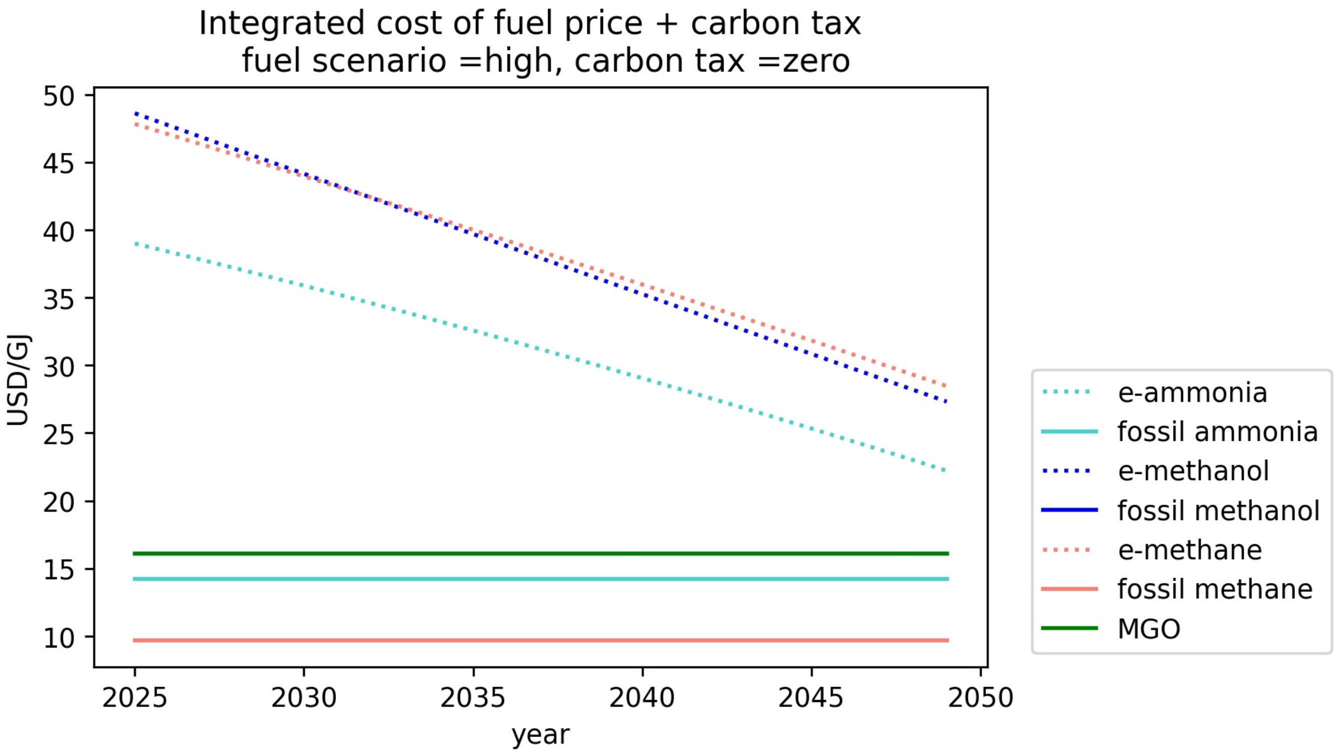


Figure A.1: Integrated fuel cost for one fuel price scenario and one carbon tax scenario. This has been calculated by applying the carbon tax on the LCA emissions of the fuel and adding these cost to the fuel cost. The renewable version of the fuel is labelled with 'SYN', the fossil version with 'F'.

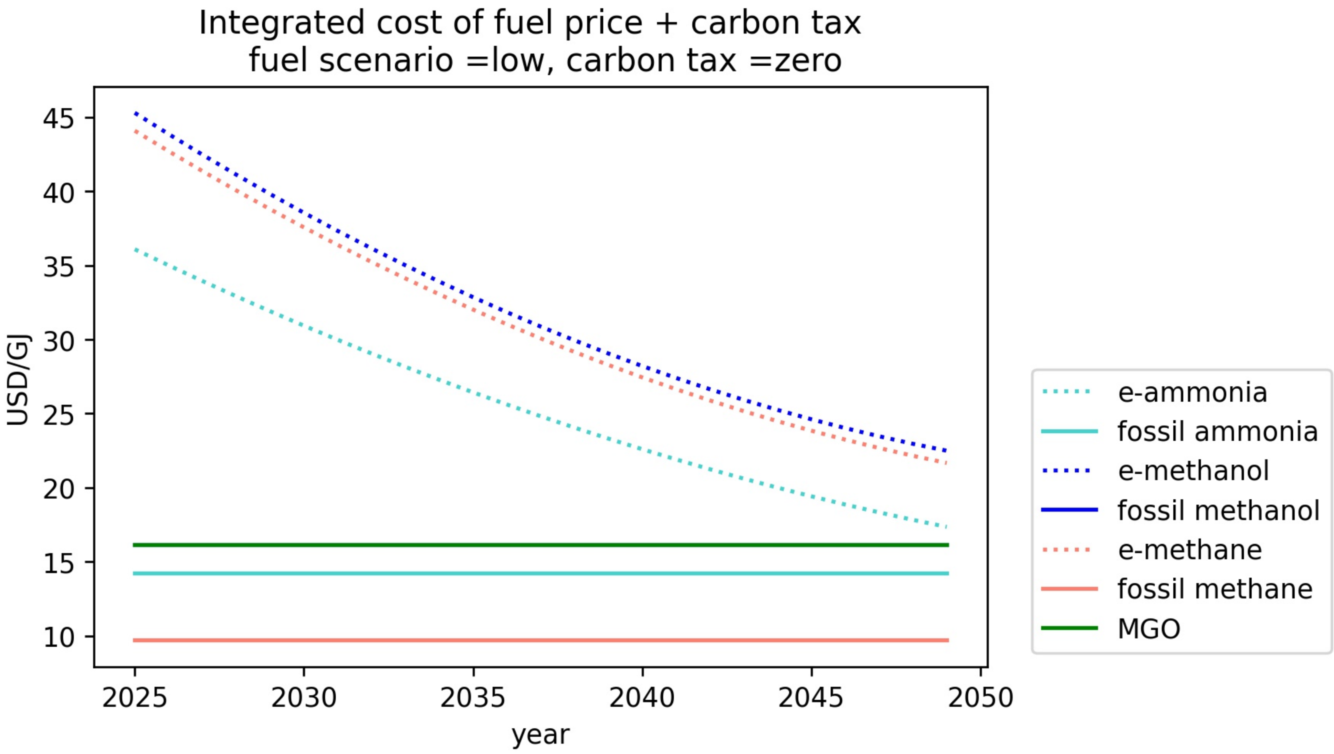


Figure A.2: Integrated fuel cost for one fuel price scenario and one carbon tax scenario. This has been calculated by applying the carbon tax on the LCA emissions of the fuel and adding these cost to the fuel cost.The renewable version of the fuel is labelled with 'SYN', the fossil version with 'F'.

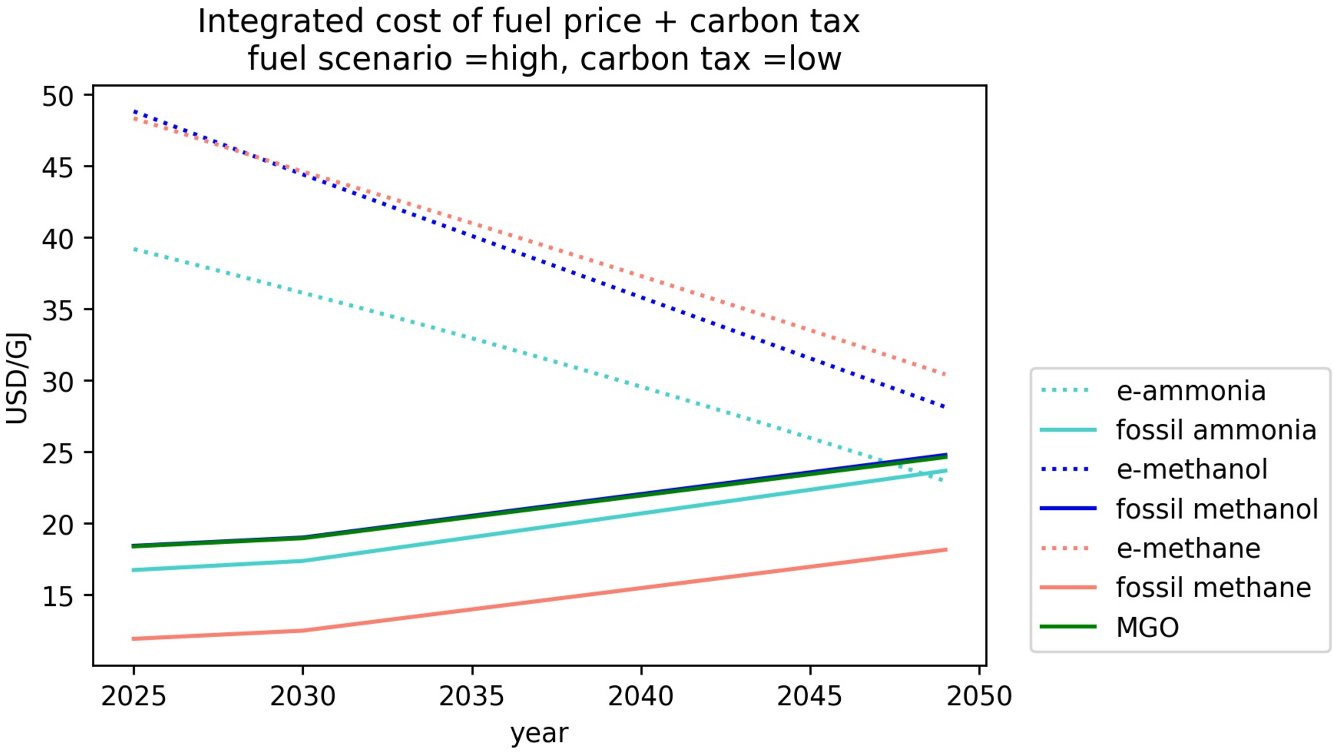


Figure A.3: Integrated fuel cost for one fuel price scenario and one carbon tax scenario. This has been calculated by applying the carbon tax on the LCA emissions of the fuel and adding these cost to the fuel cost.The renewable version of the fuel is labelled with 'SYN', the fossil version with 'F'.

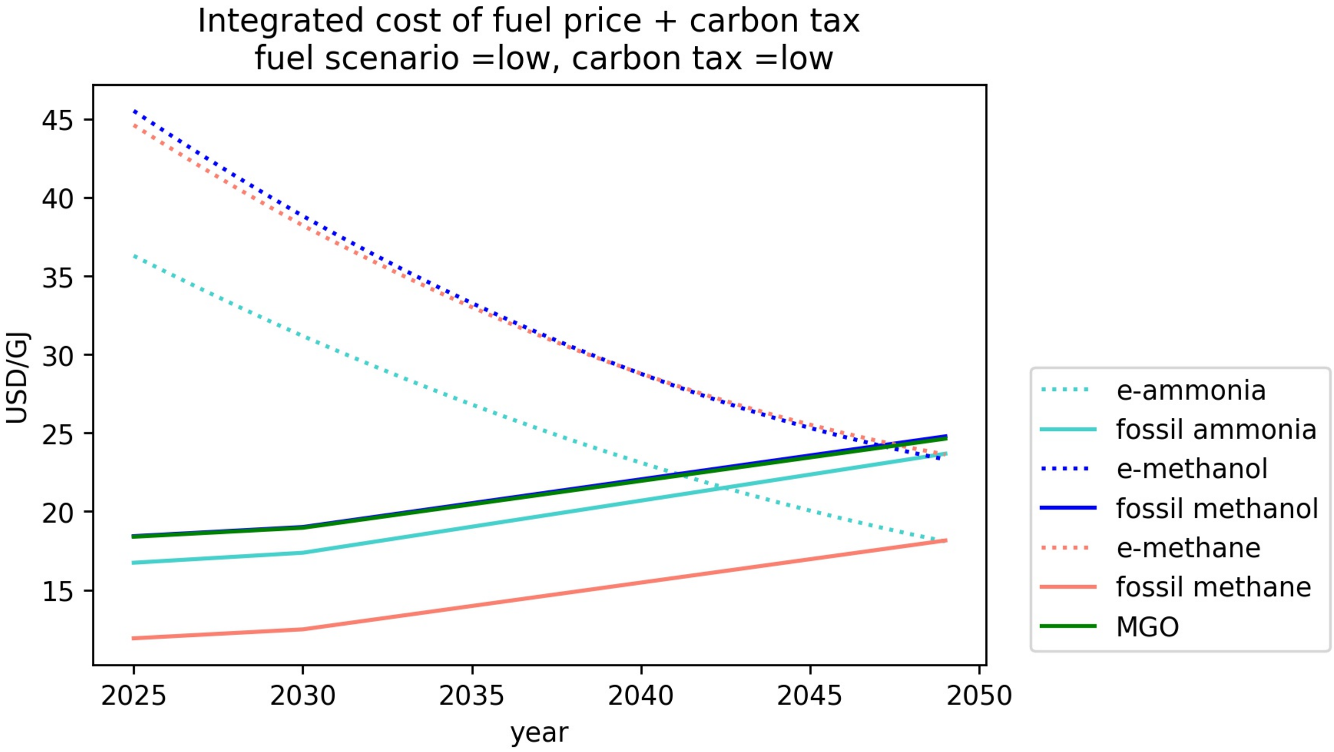


Figure A.4: Integrated fuel cost for one fuel price scenario and one carbon tax scenario. This has been calculated by applying the carbon tax on the LCA emissions of the fuel and adding these cost to the fuel cost.The renewable version of the fuel is labelled with 'SYN', the fossil version with 'F'.

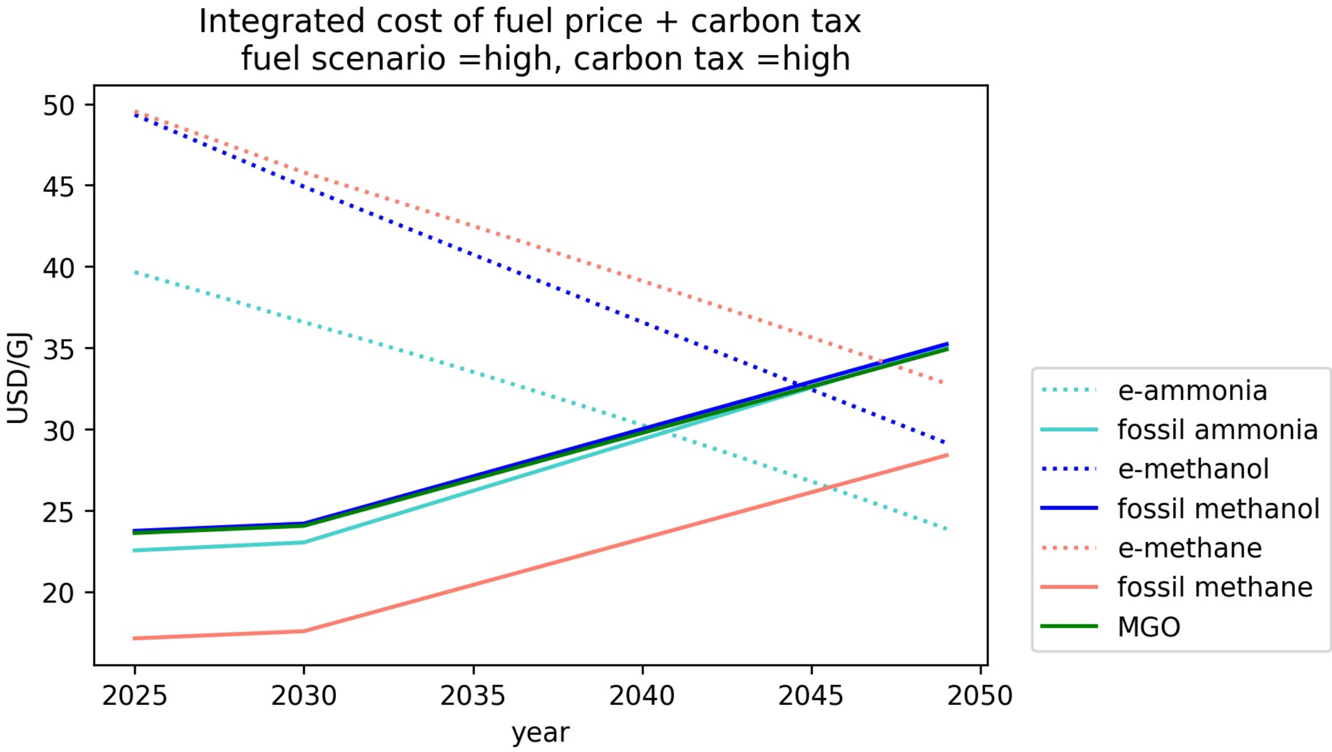


Figure A.5: Integrated fuel cost for one fuel price scenario and one carbon tax scenario. This has been calculated by applying the carbon tax on the LCA emissions of the fuel and adding these cost to the fuel cost.The renewable version of the fuel is labelled with 'SYN', the fossil version with 'F'.

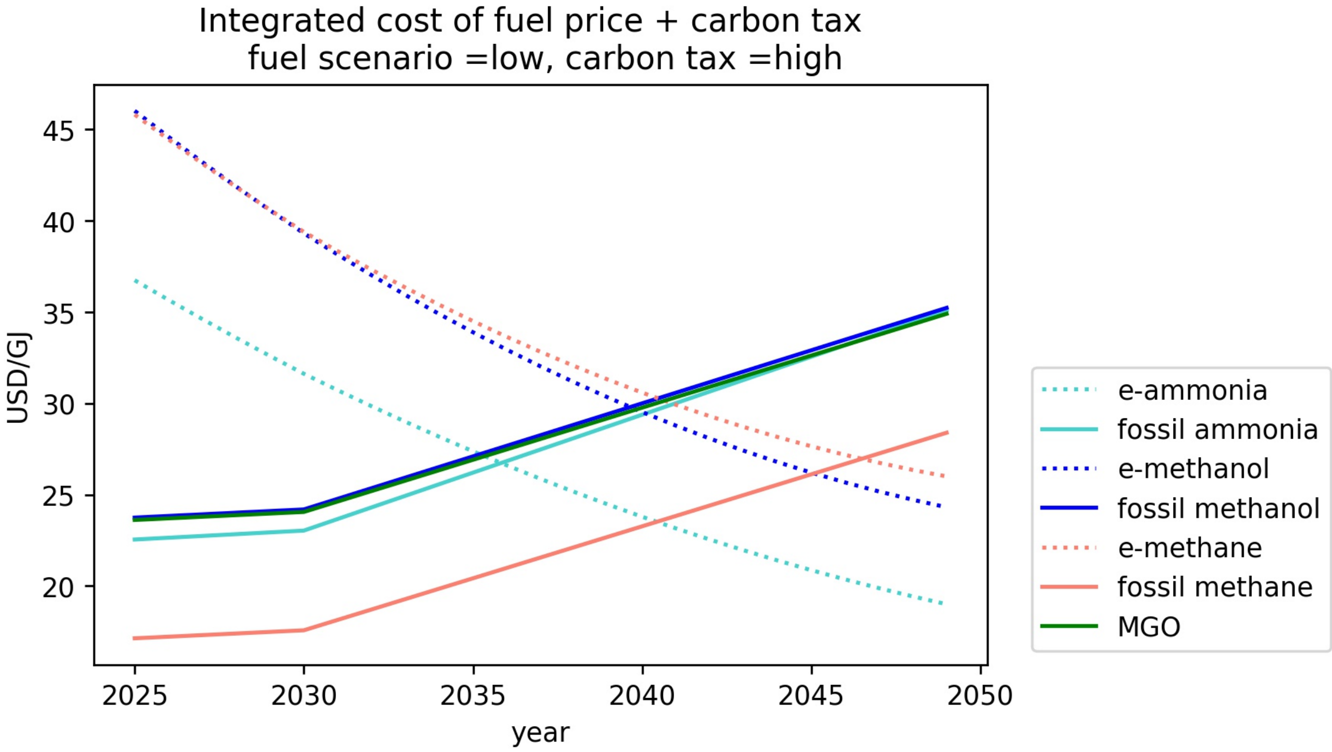


Figure A.6: Integrated fuel cost for one fuel price scenario and one carbon tax scenario. This has been calculated by applying the carbon tax on the LCA emissions of the fuel and adding these cost to the fuel cost.The renewable version of the fuel is labelled with 'SYN', the fossil version with 'F'.

B

Trendlines

This appendix contains the trendlines as determined for chapter 5 based on data retrieved from Clarksons Intelligence.

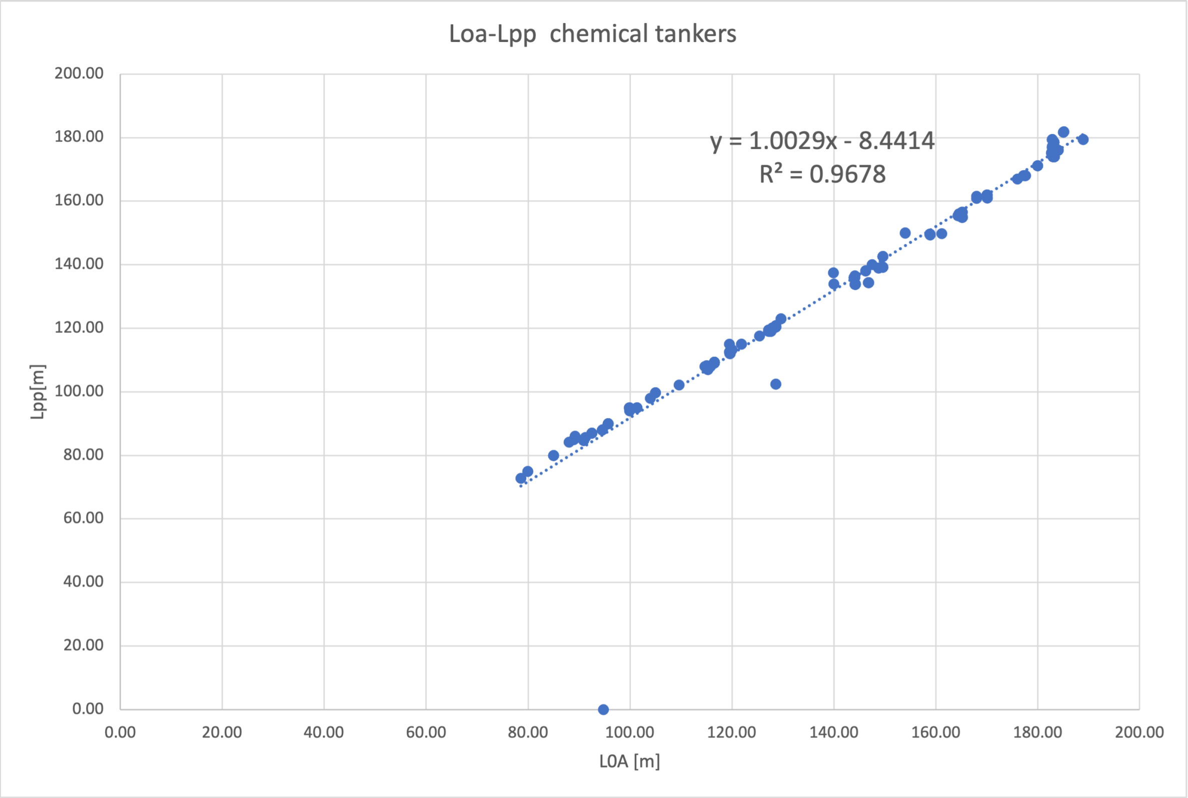


Figure B.1: Trendline for the correlation between $L_o a$ and L_{pp}

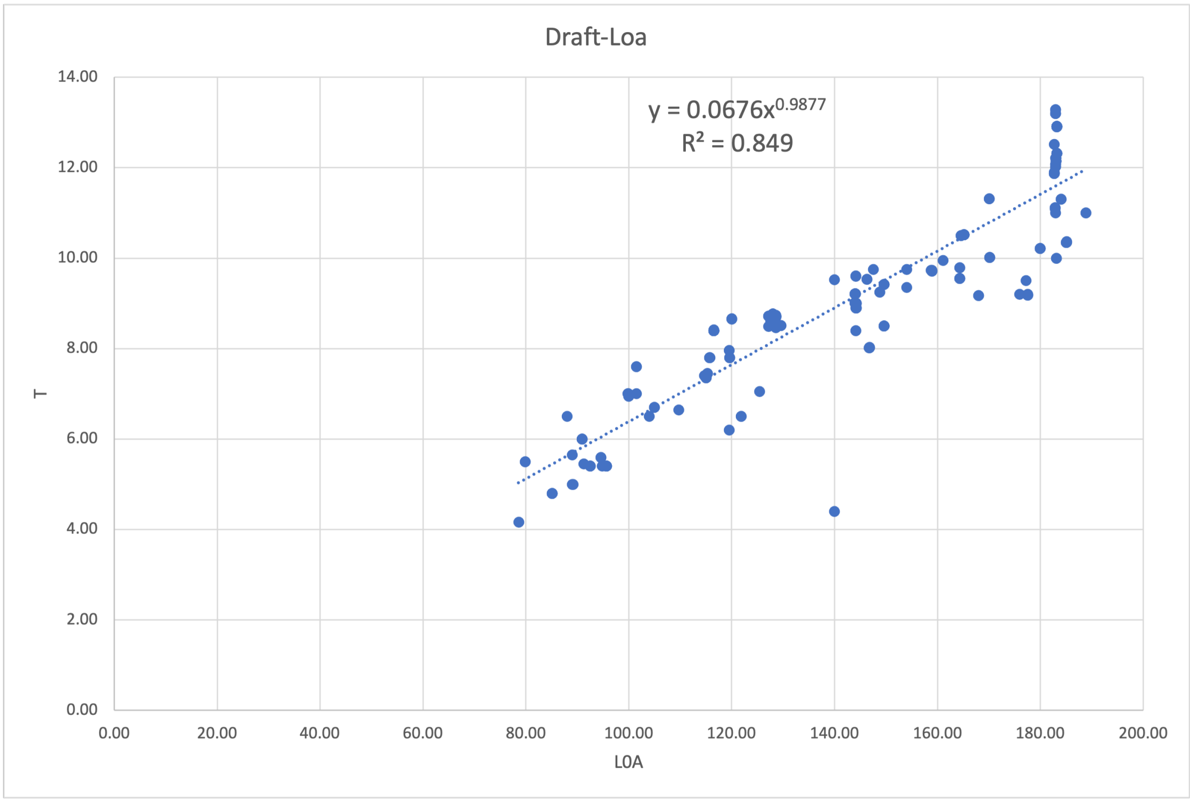
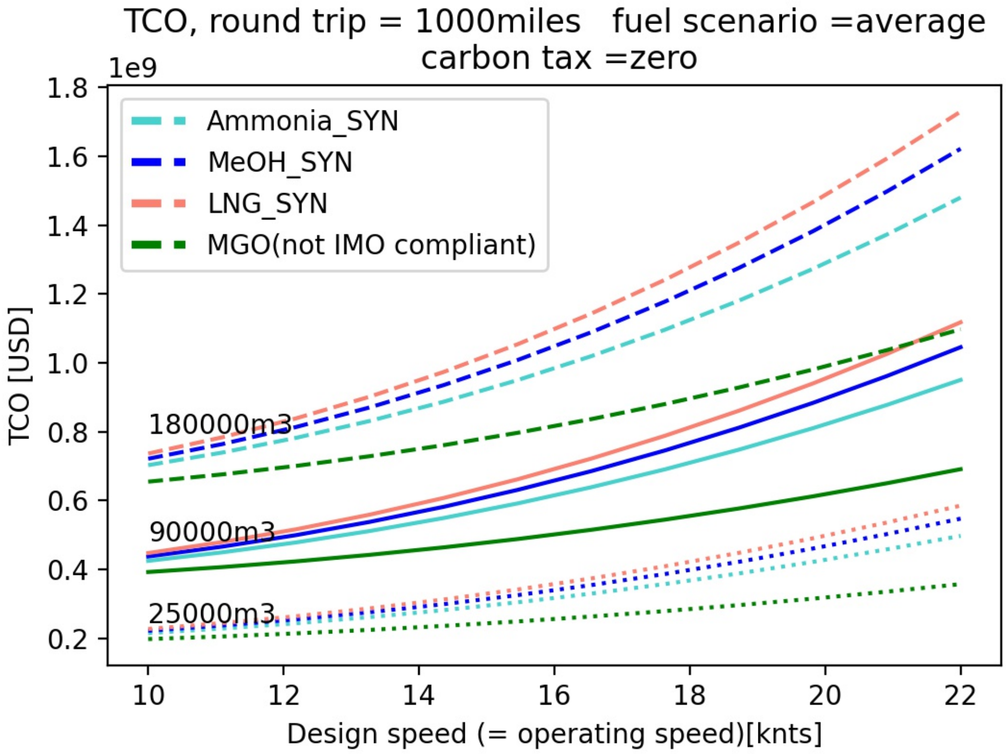


Figure B.2: Trendline for the correlation between the draft(T) and L_{oa}

C

Complete overview of the results of chapter 7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1e9
Ammonia_SYN
MeOH_SYN
LNG_SYN
MGO(not IMO compliant)
180000m3
90000m3
25000m3
TCO [USD]
1.8
1.6
1.4
1.2
1.0
0.8
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0.4
0.2
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22
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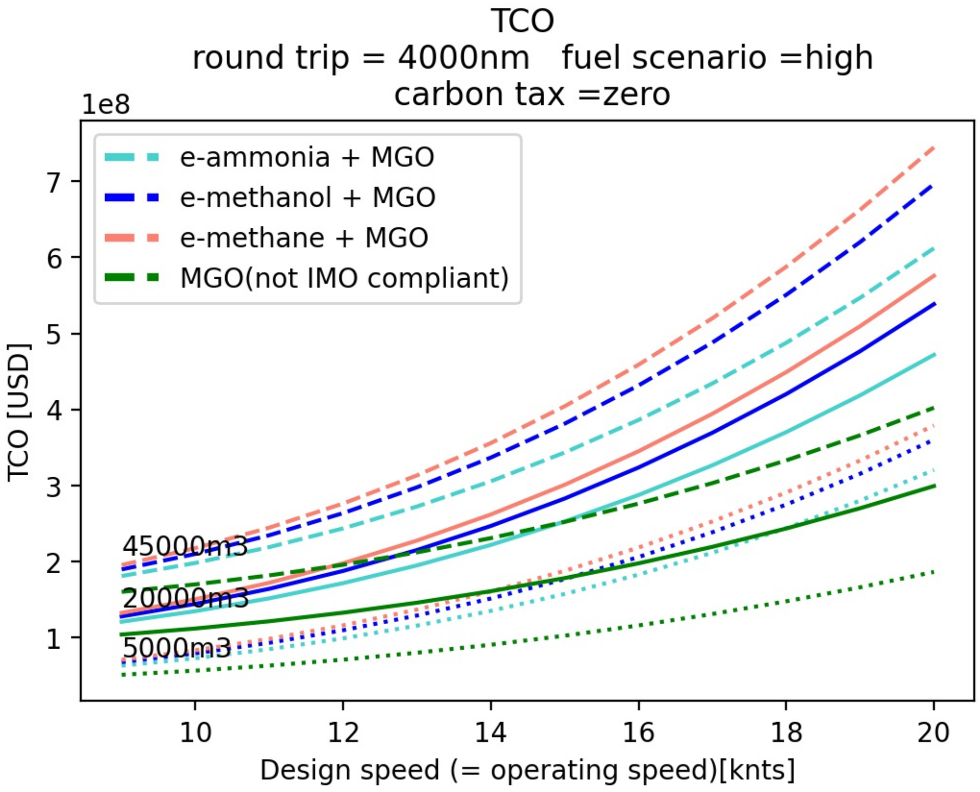
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45000m3
20000m3
5000m3
TCO [USD]
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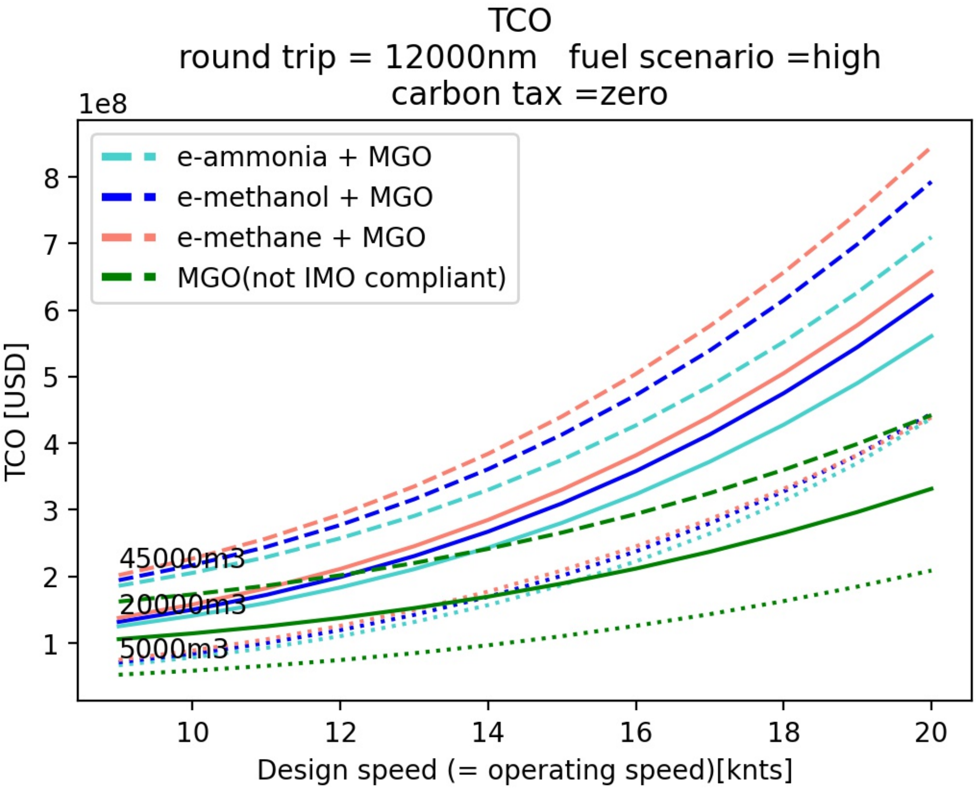
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MGO(not IMO compliant)
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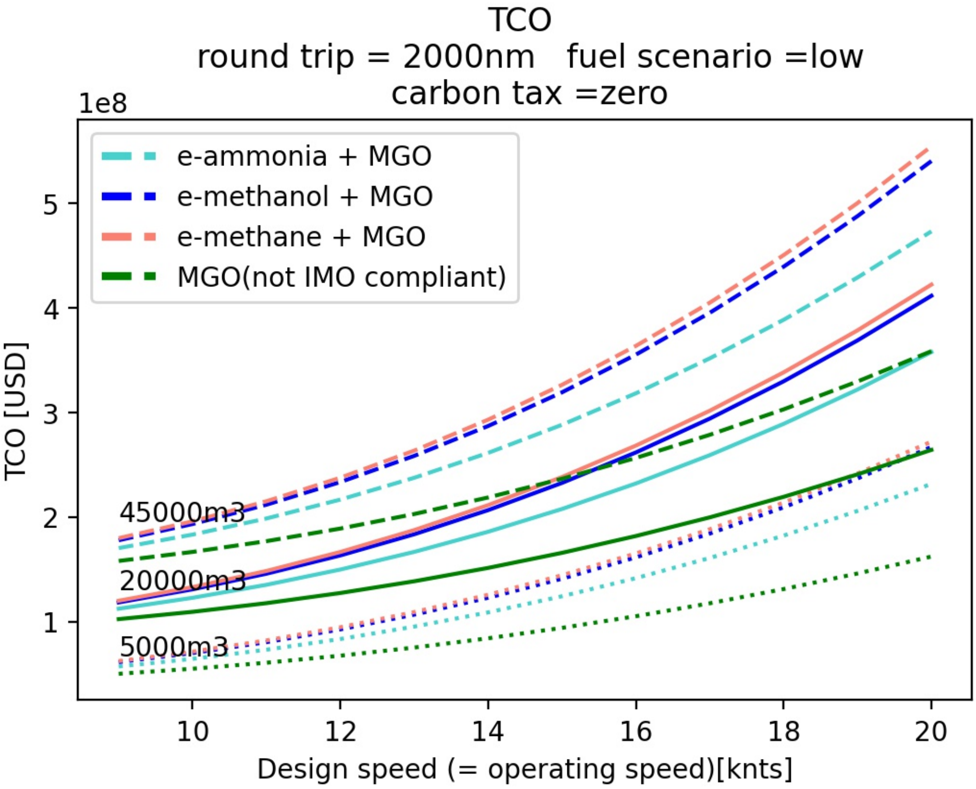
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MGO(not IMO compliant)
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TCO [USD]
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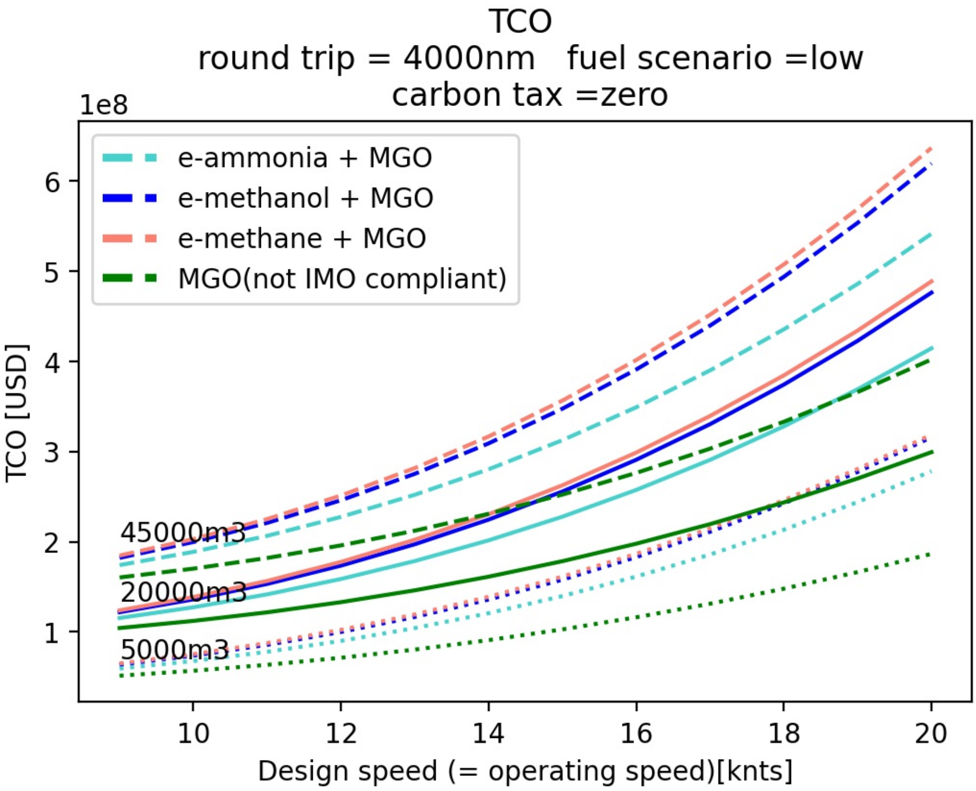
Design speed (= operating speed)[knts]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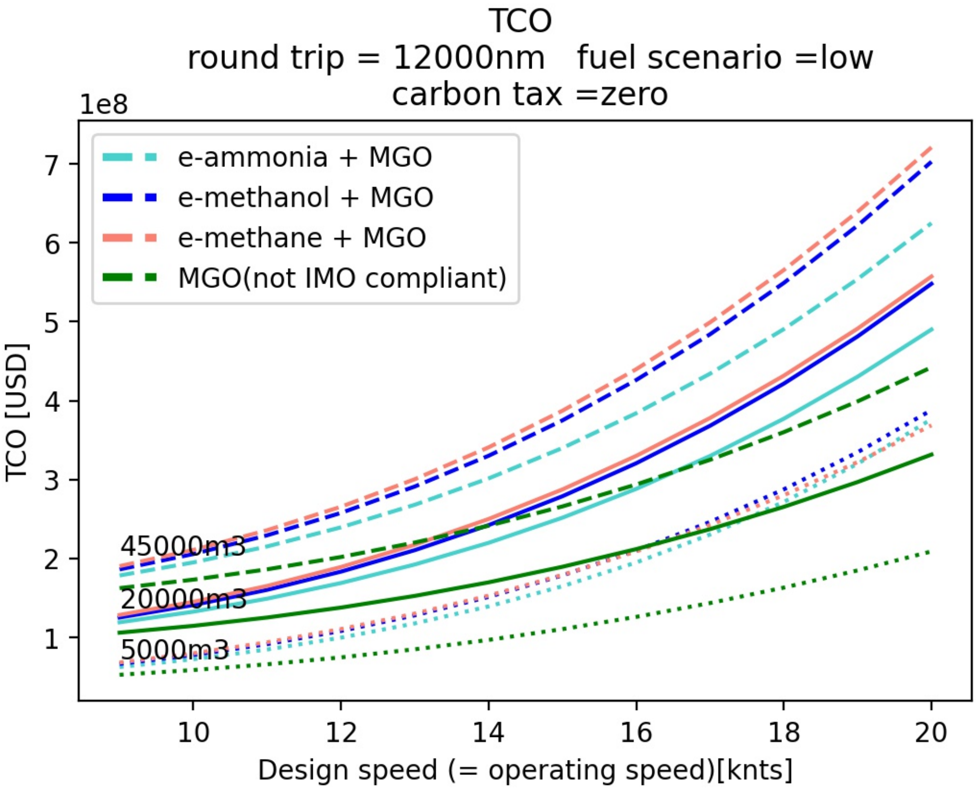
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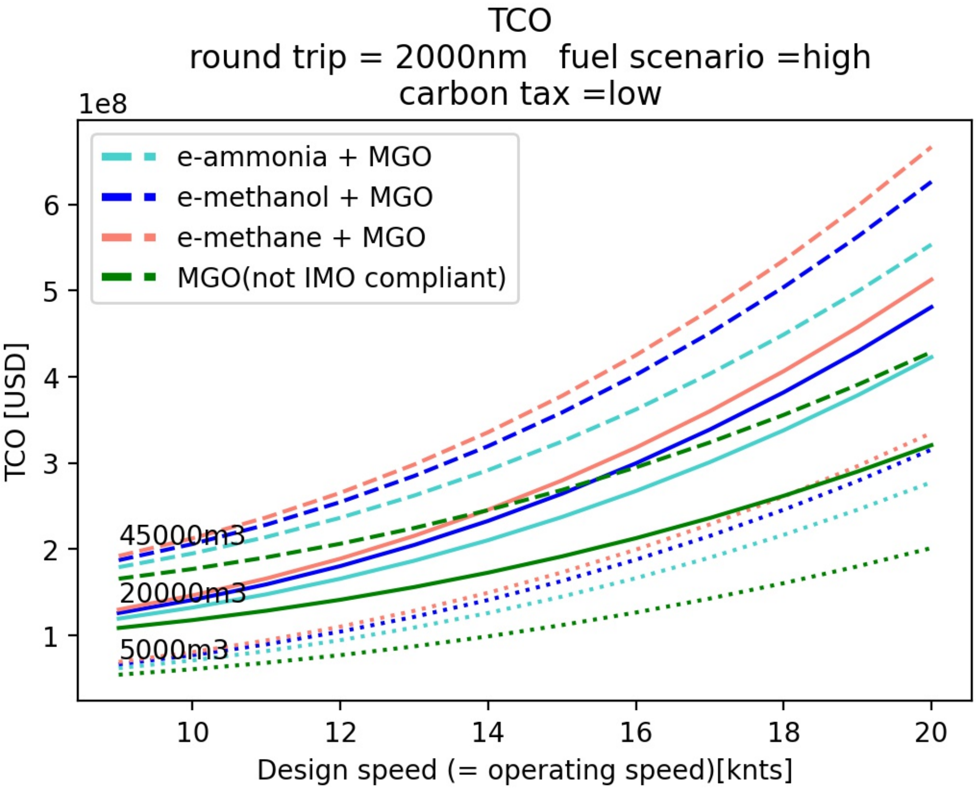
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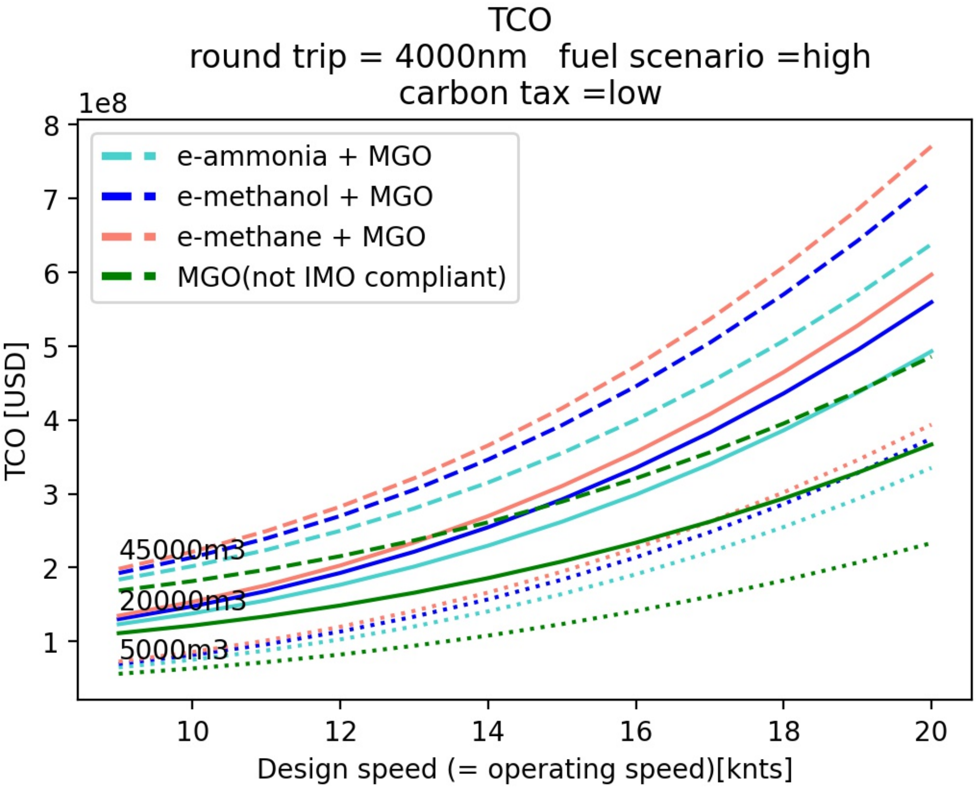
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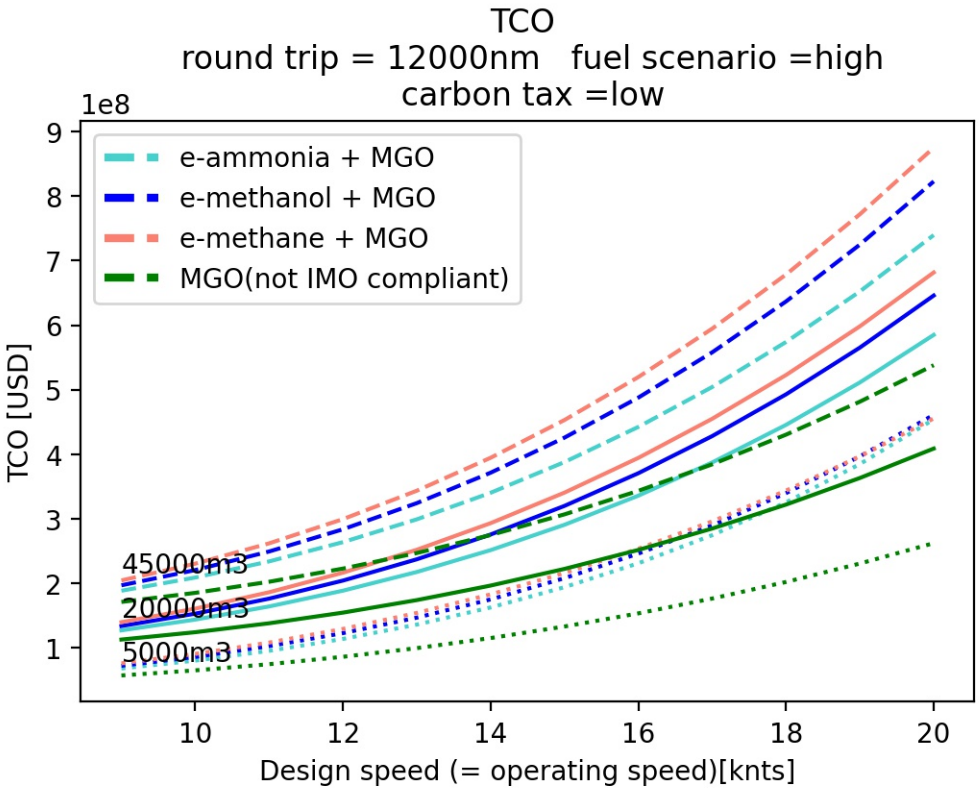
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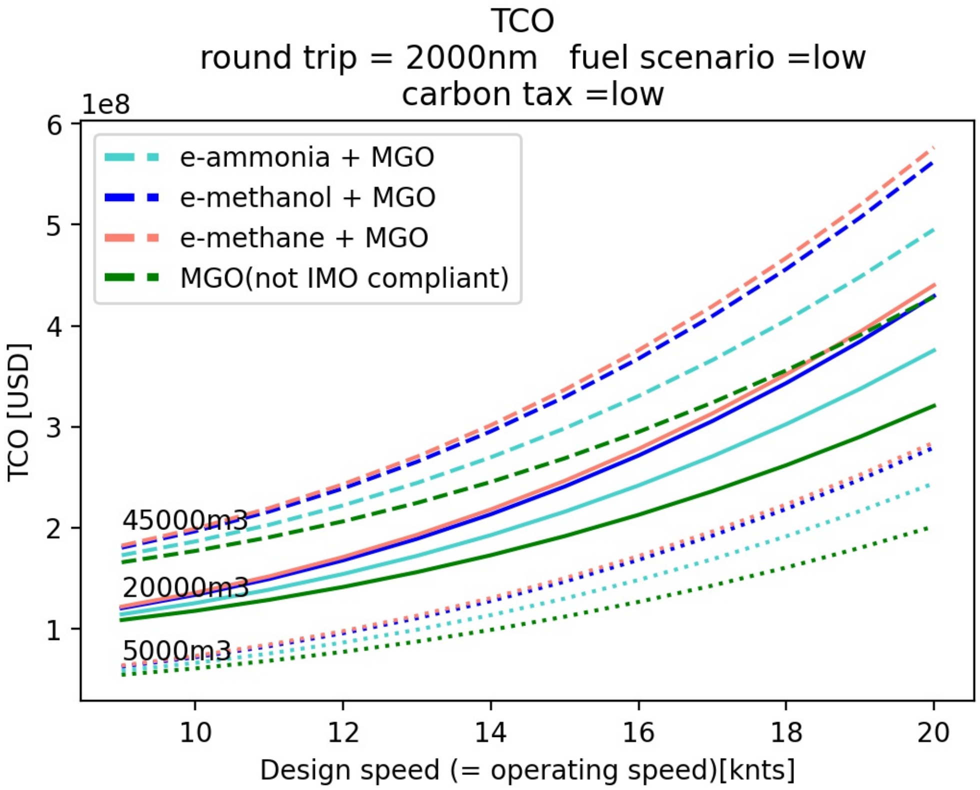
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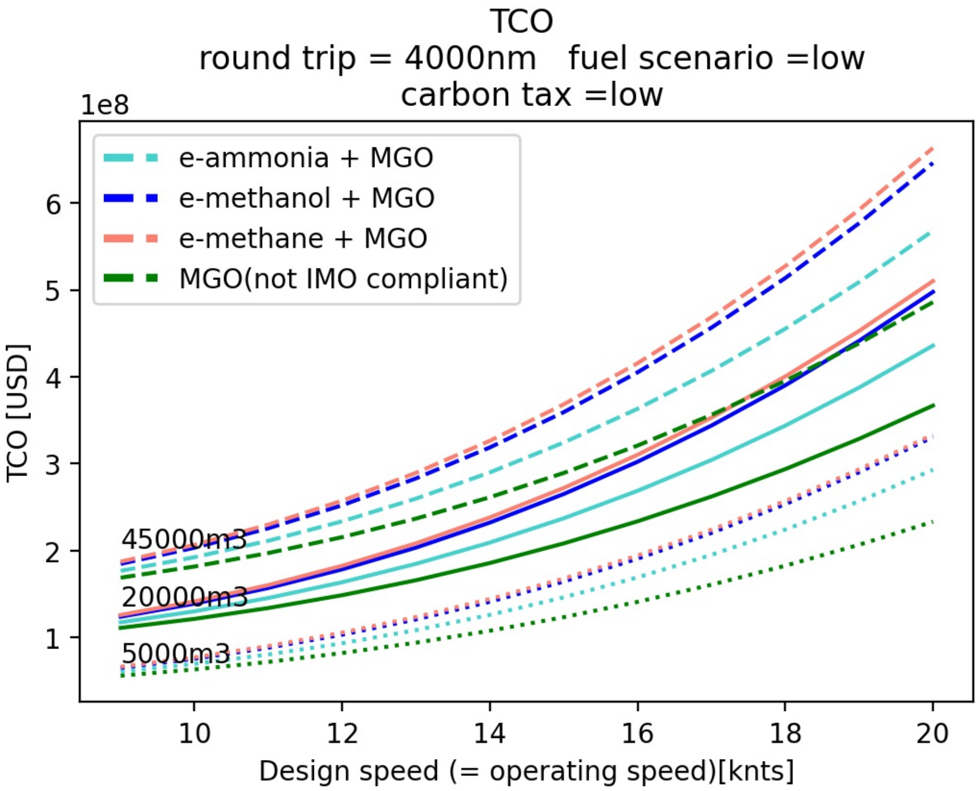
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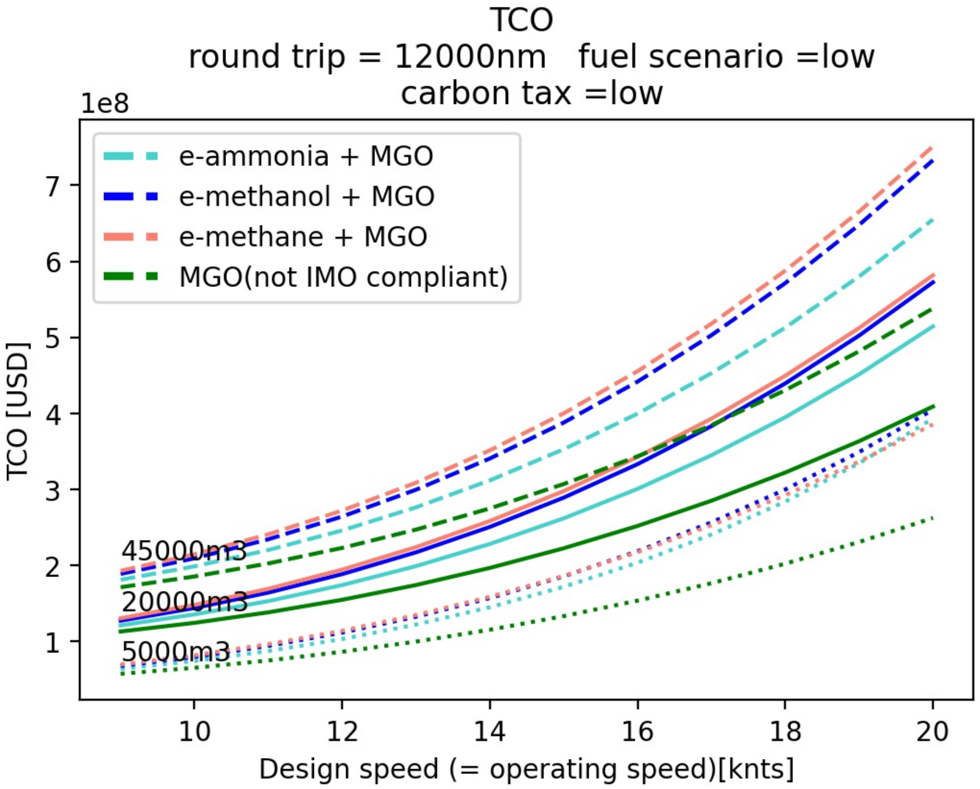
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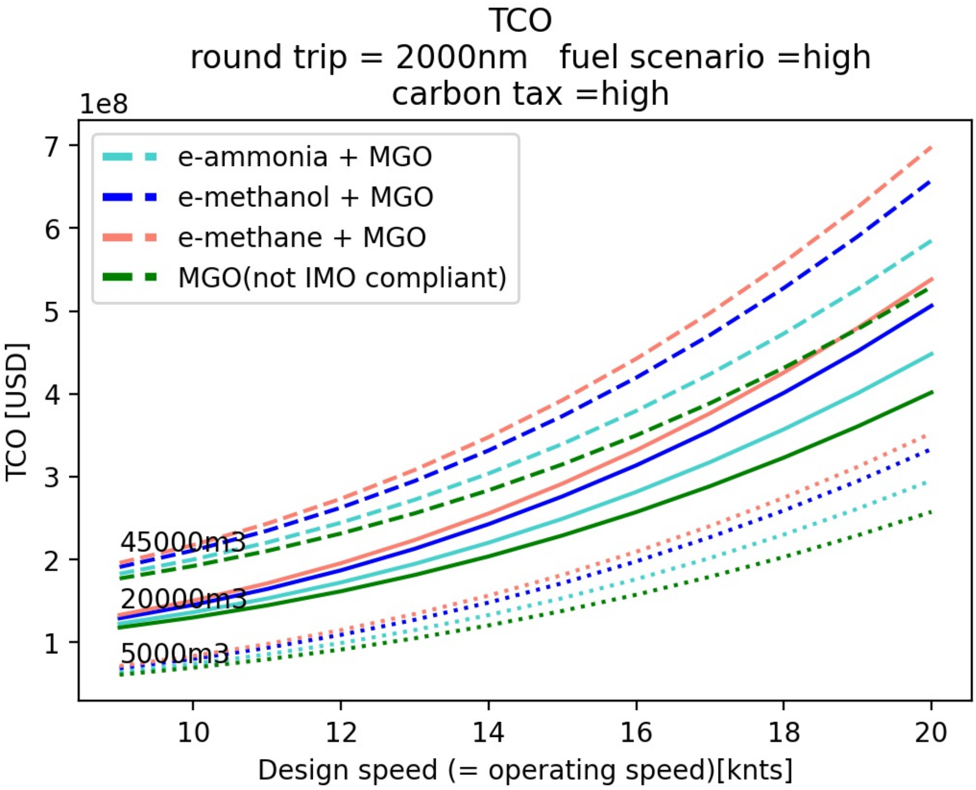
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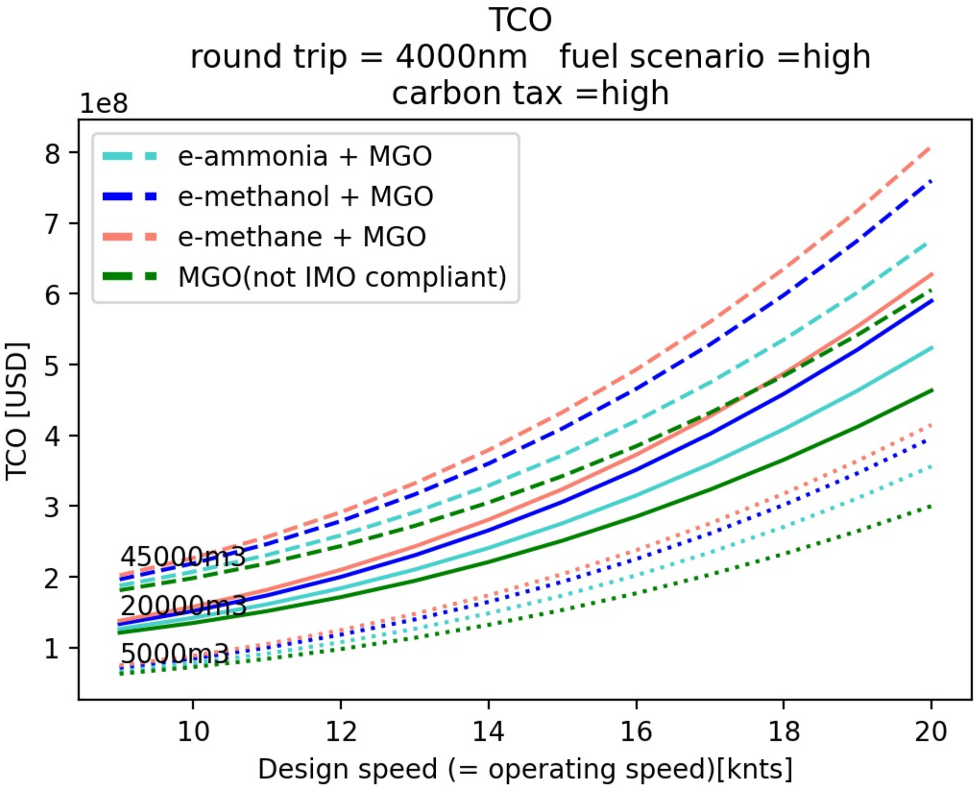
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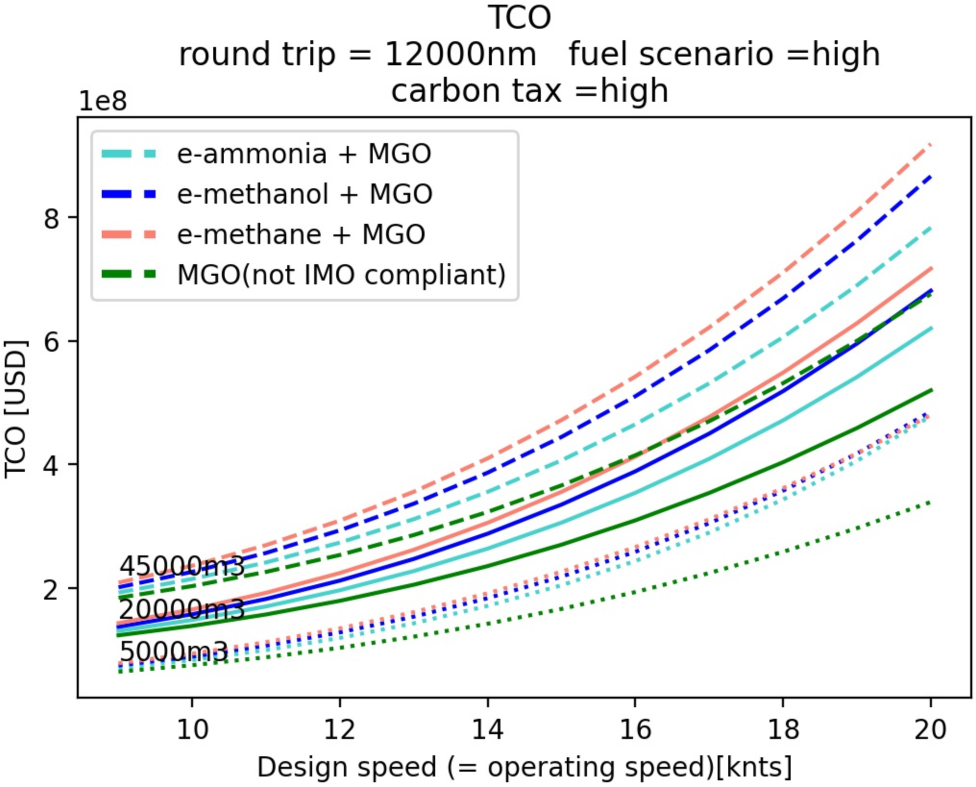
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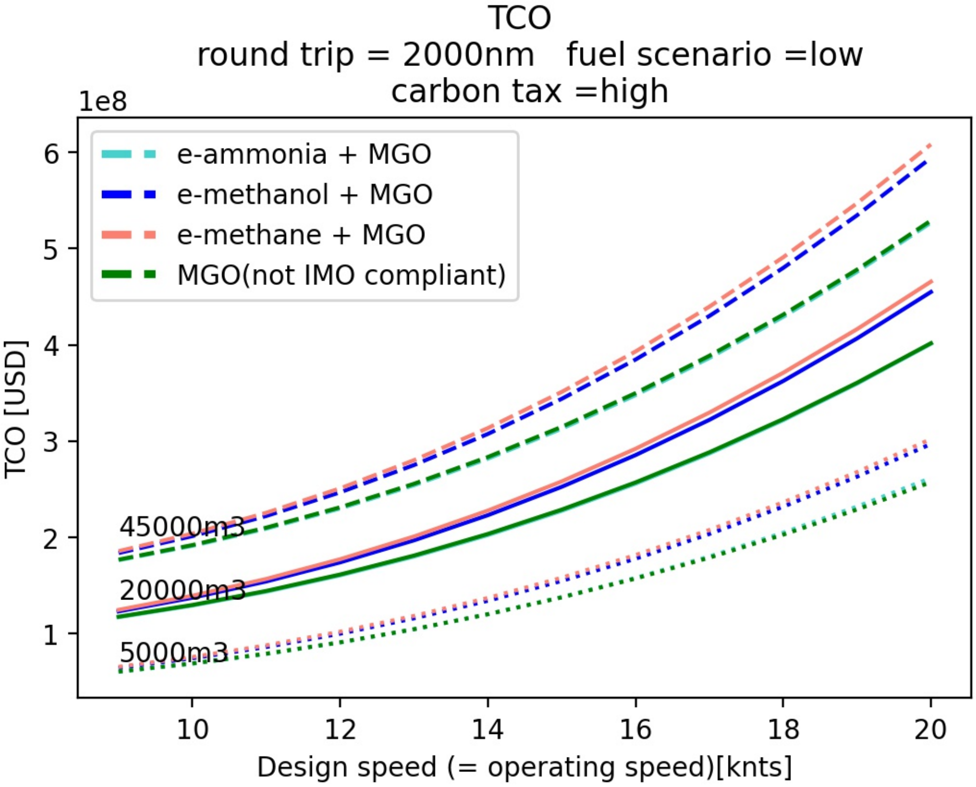
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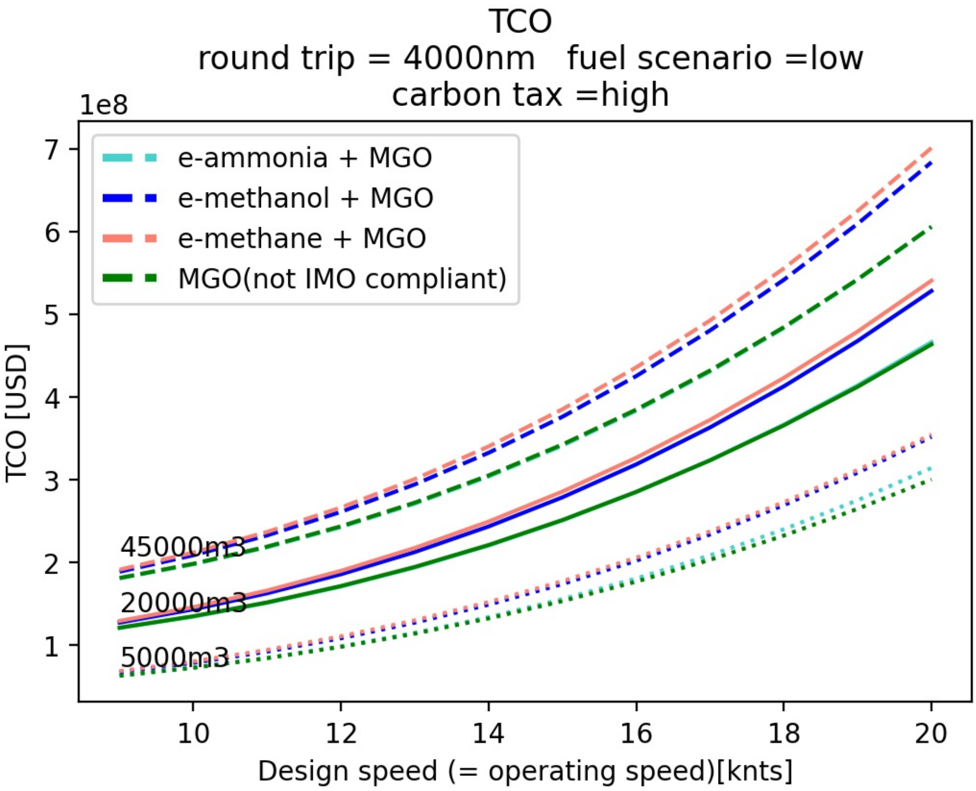
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e-methanol + MGO
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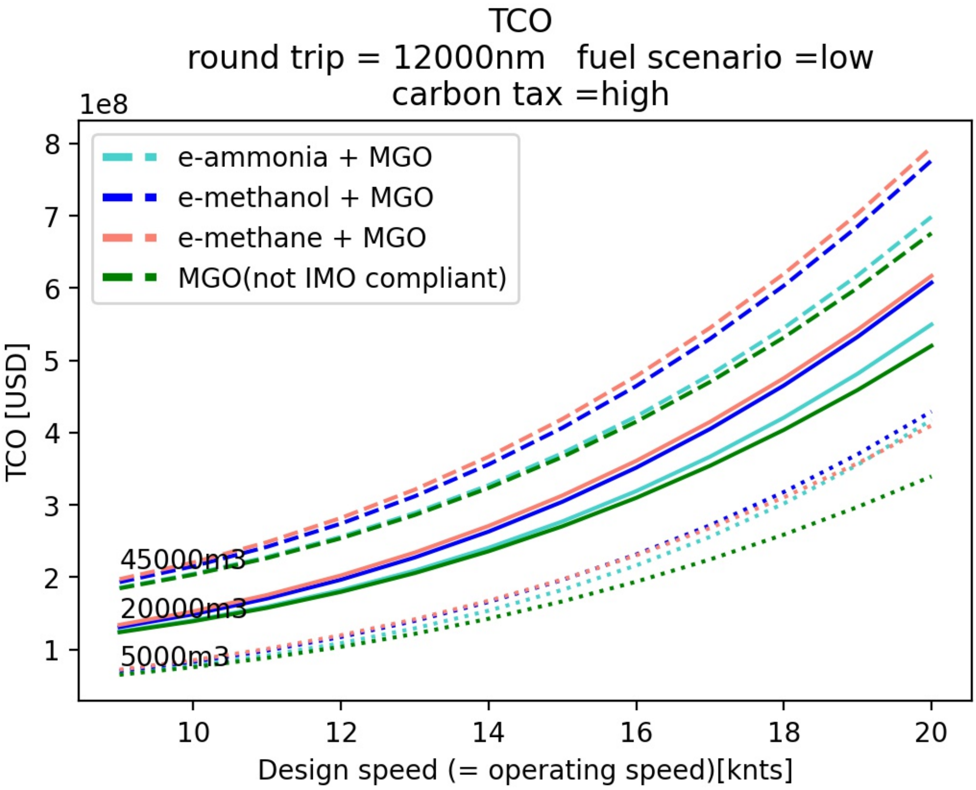
Design speed (= operating speed)[knts]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e-methanol + MGO
e-methane + MGO
MGO(not IMO compliant)
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Design speed (= operating speed)[knts]

D

Complete overview of the results of chapter 8

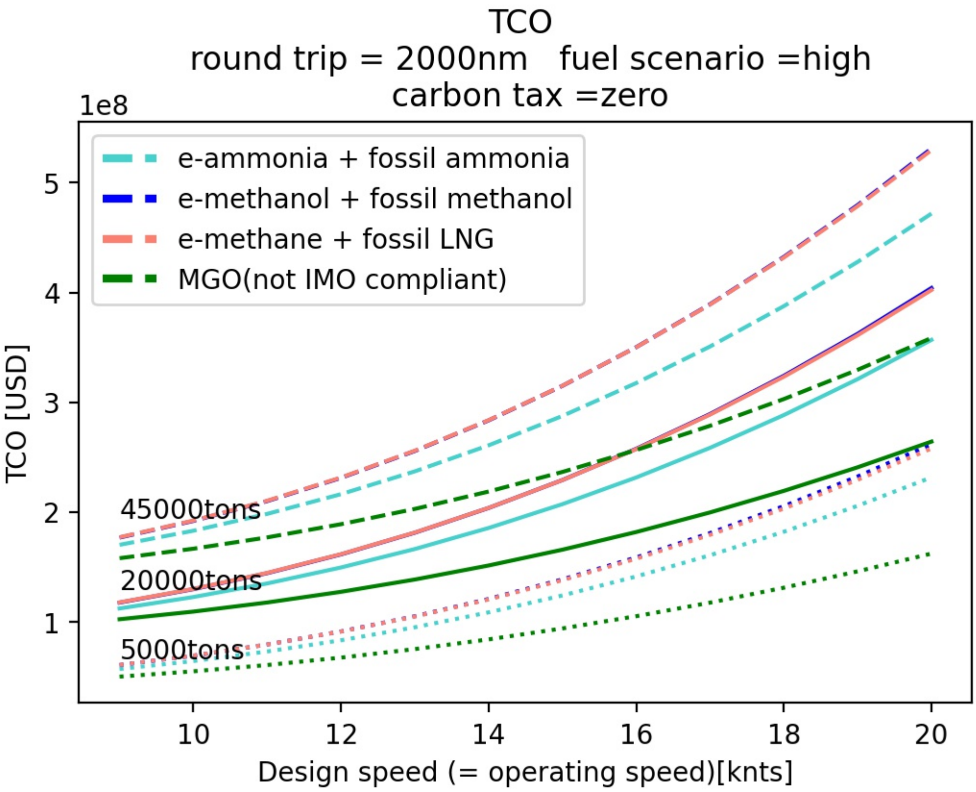


Figure D.1

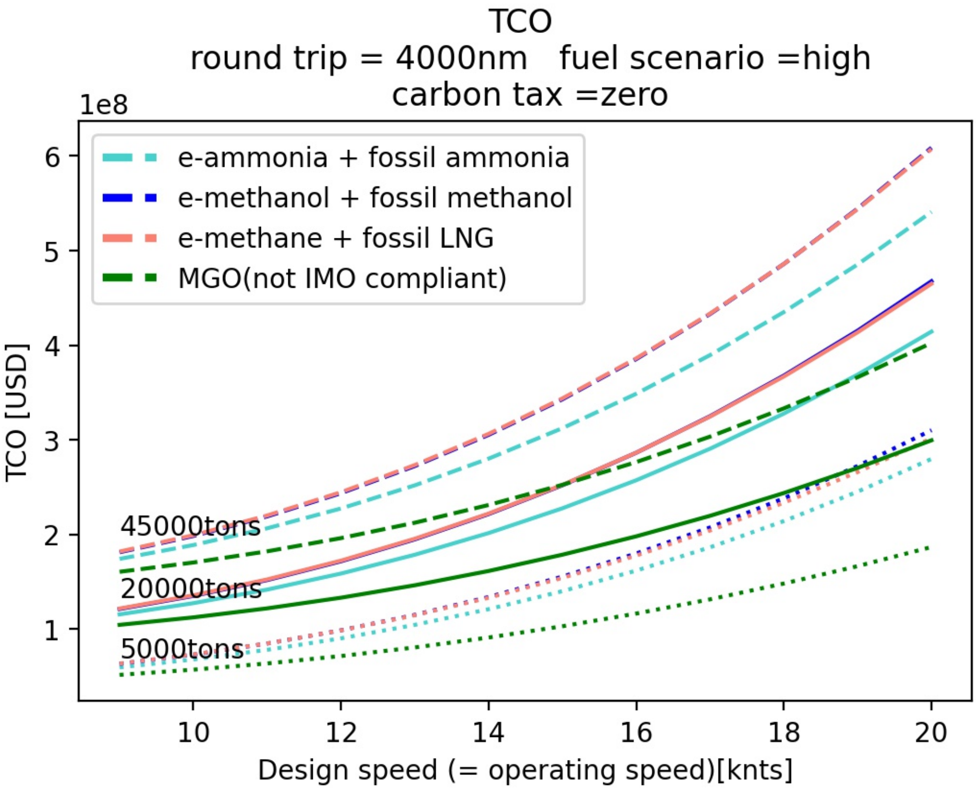


Figure D.2

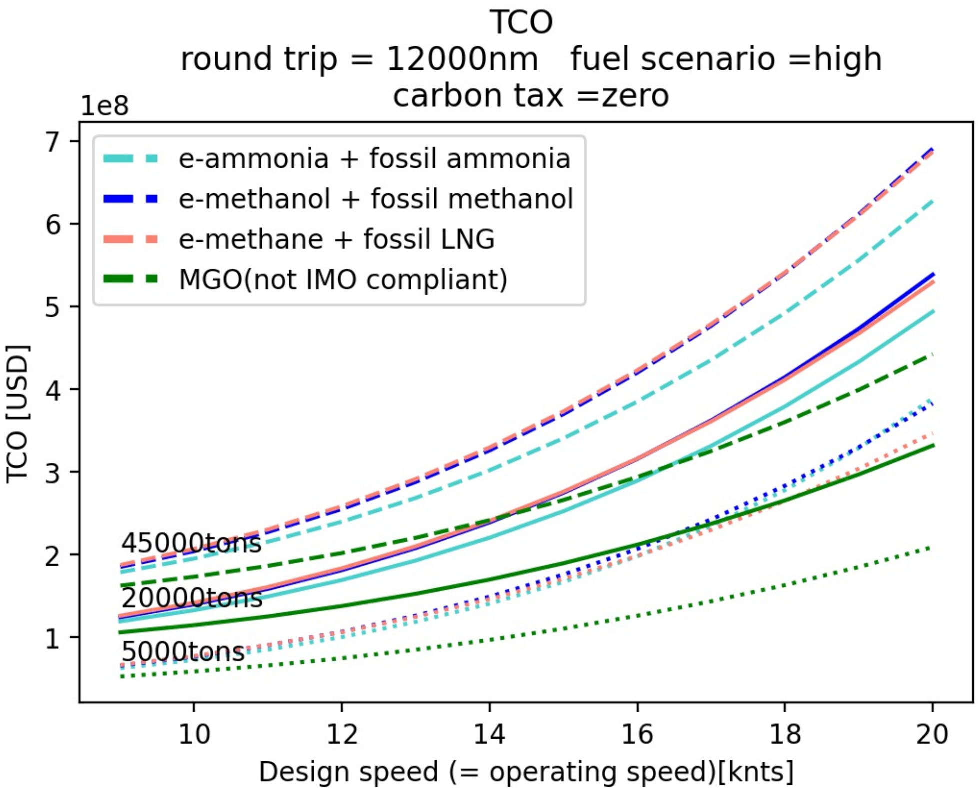
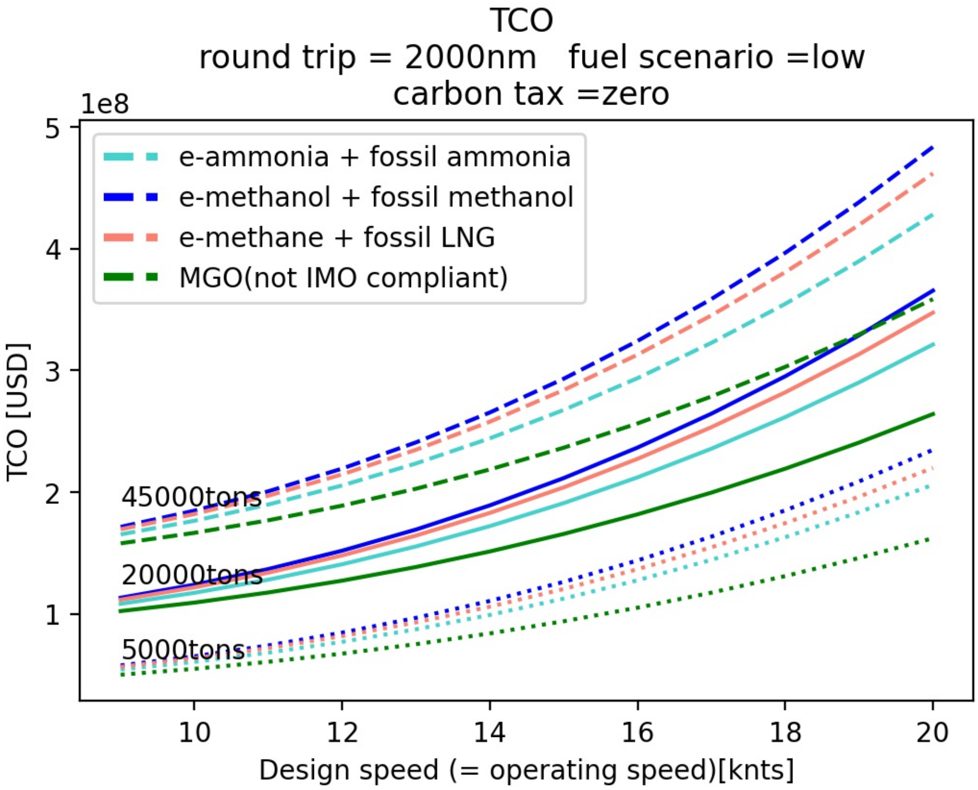


Figure D.3



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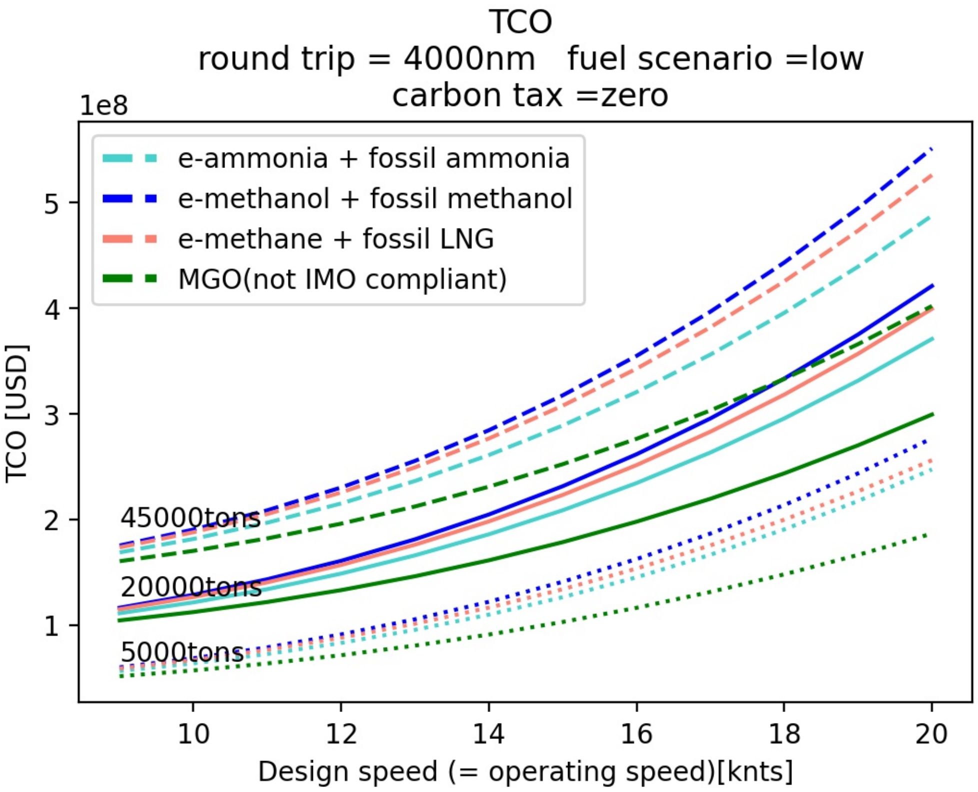

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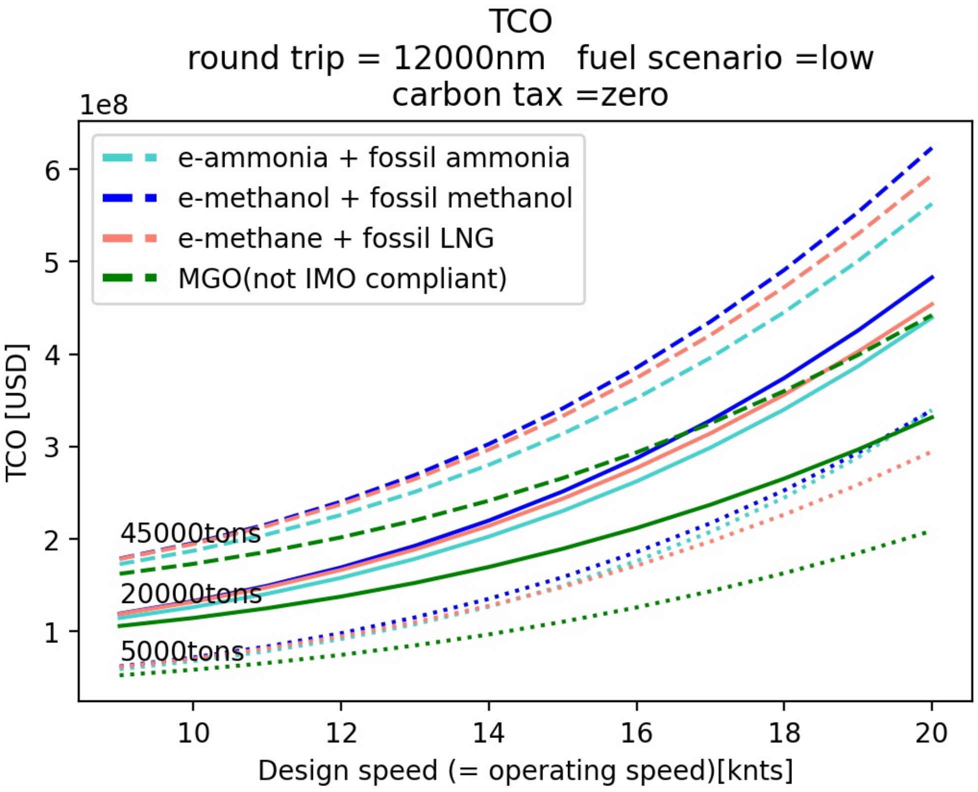

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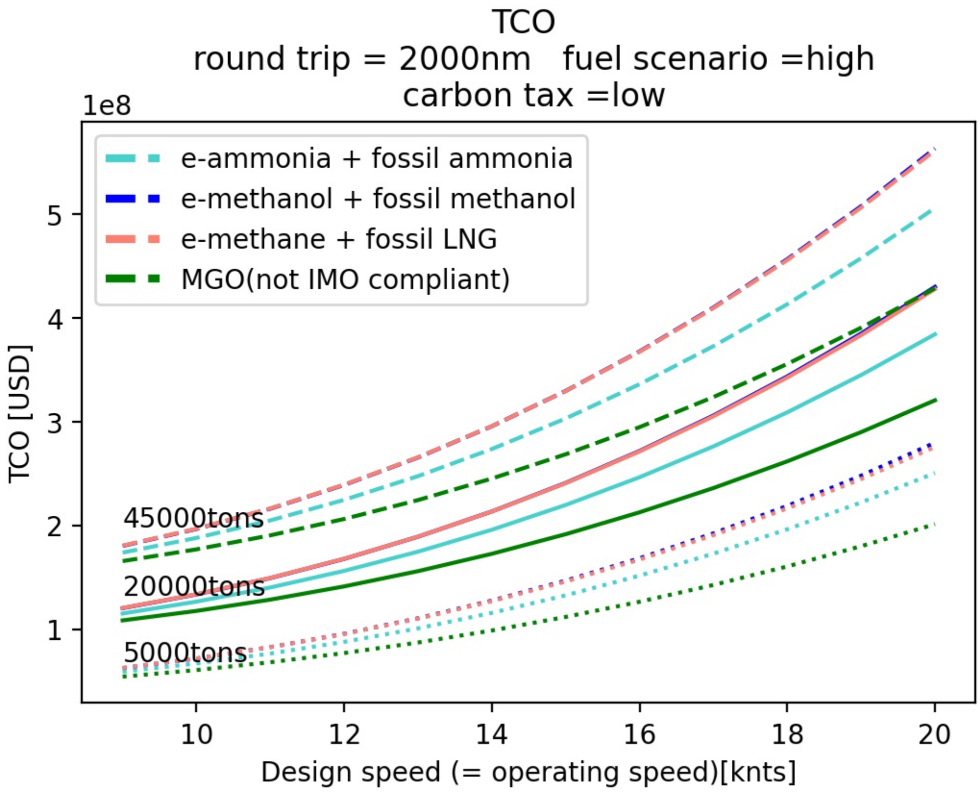

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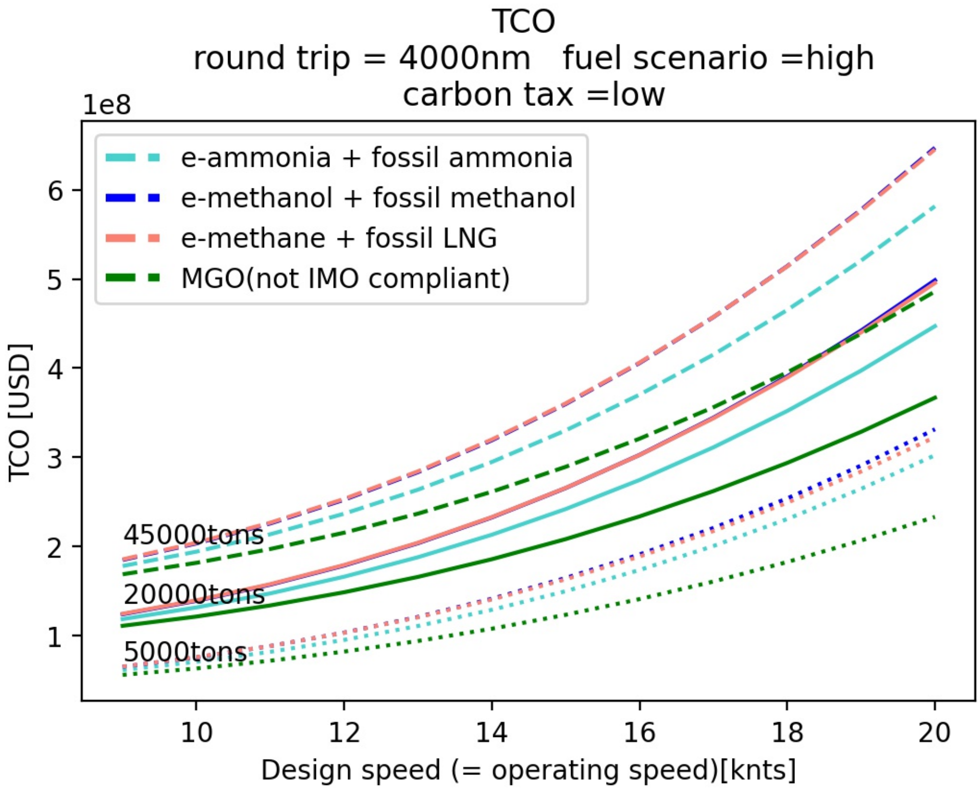

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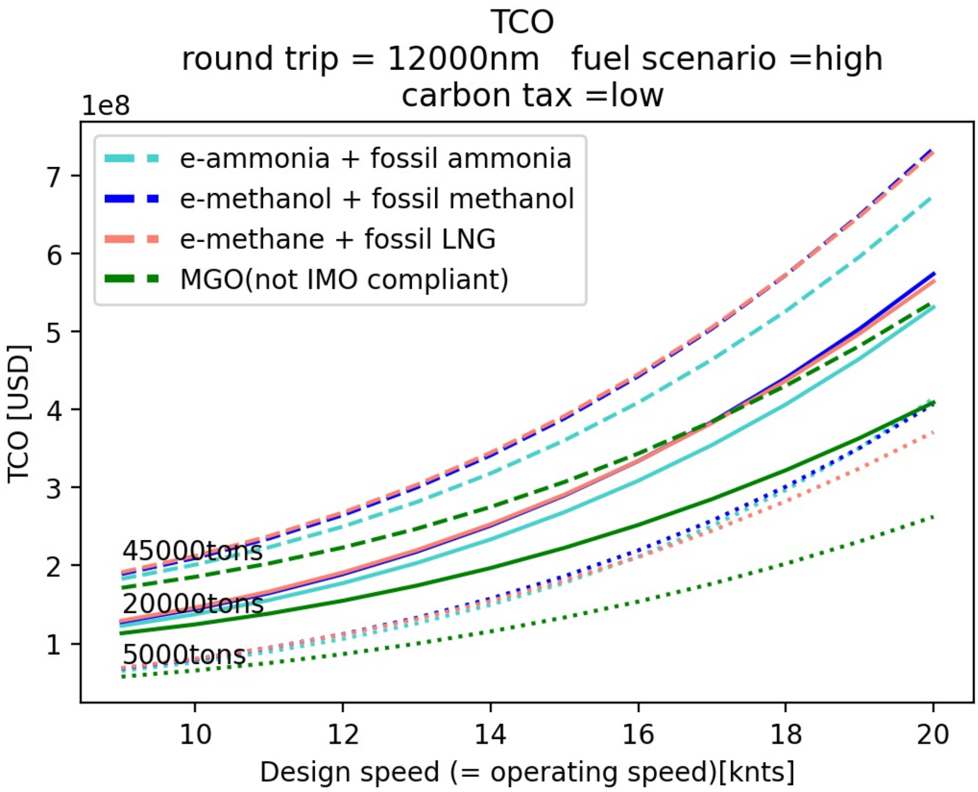

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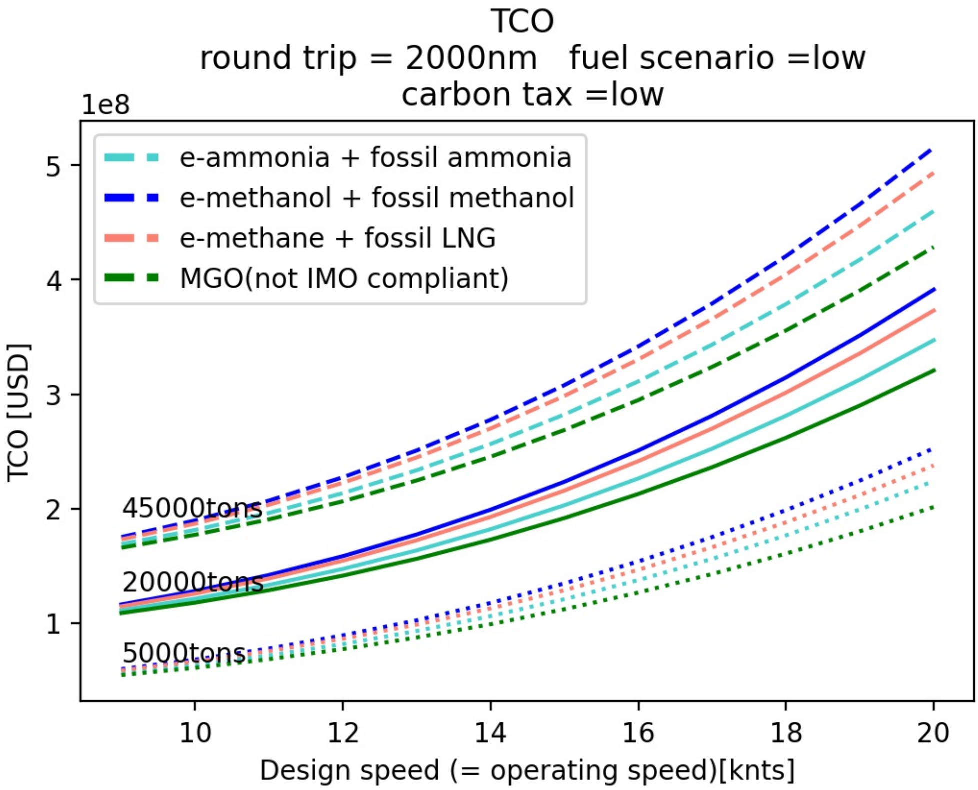

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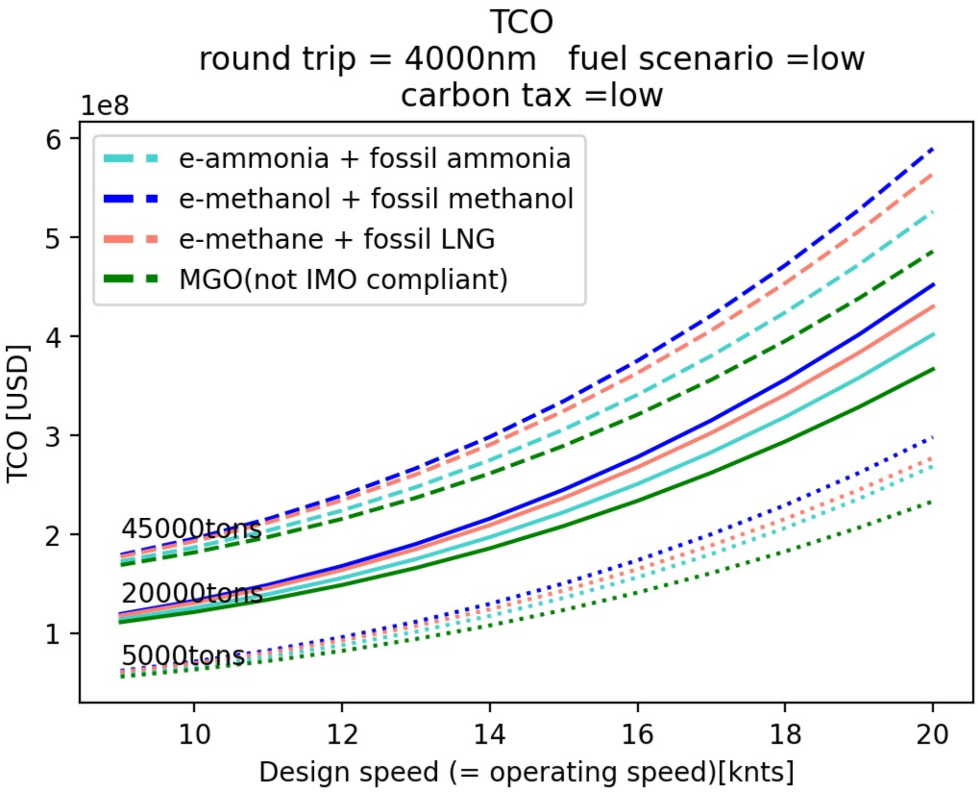

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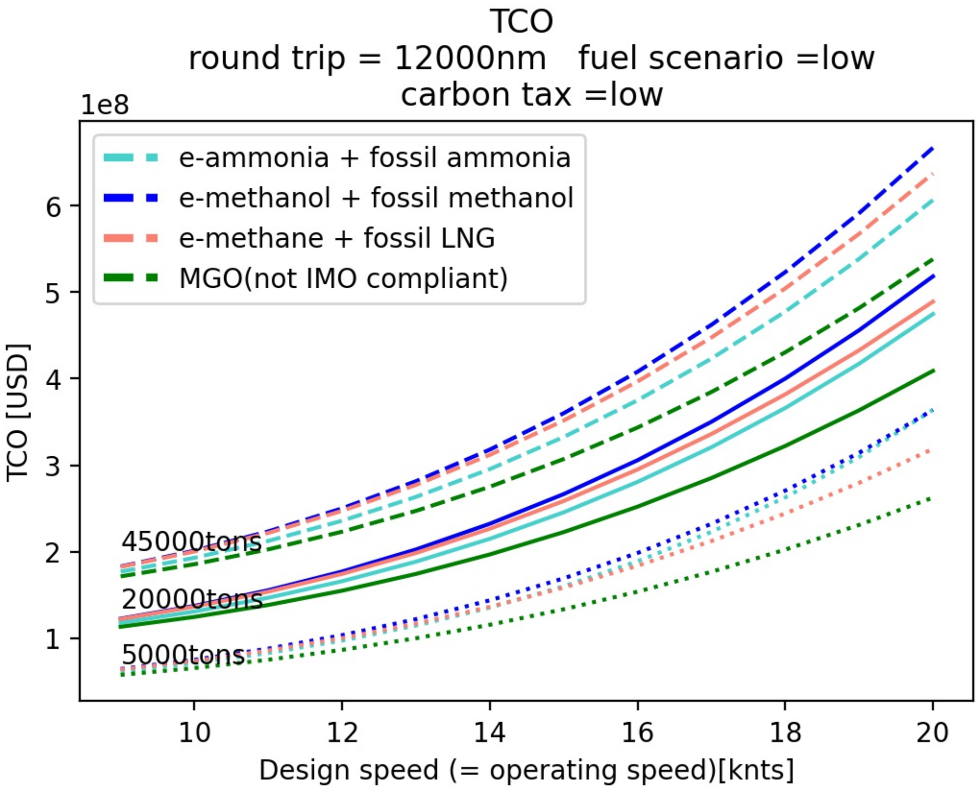

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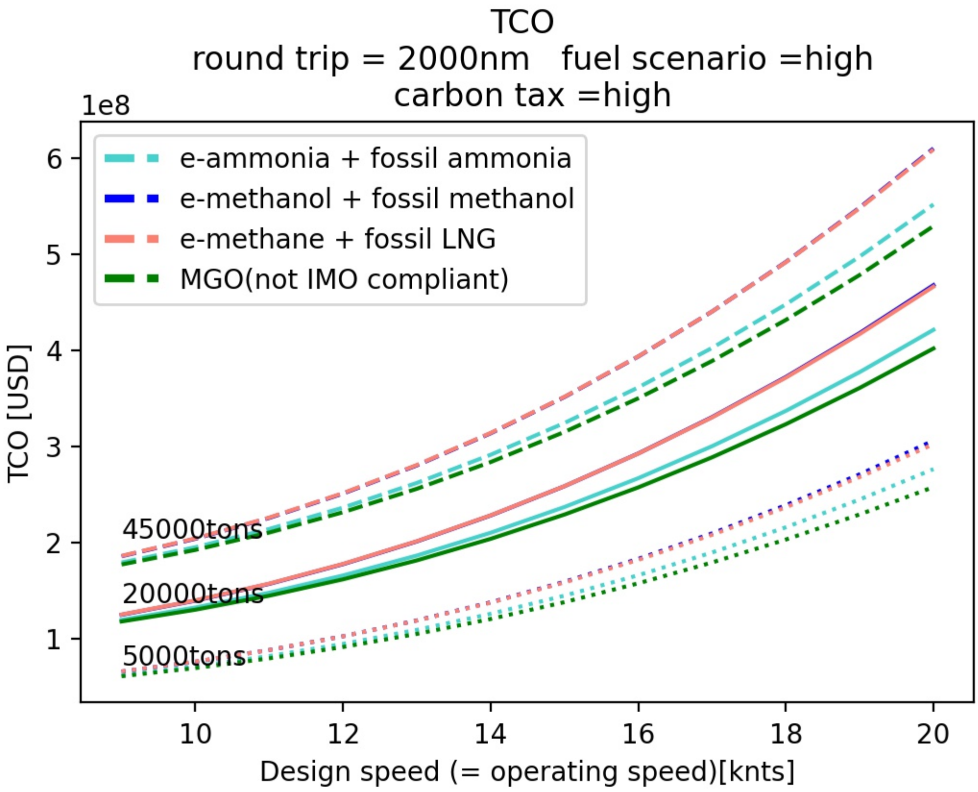

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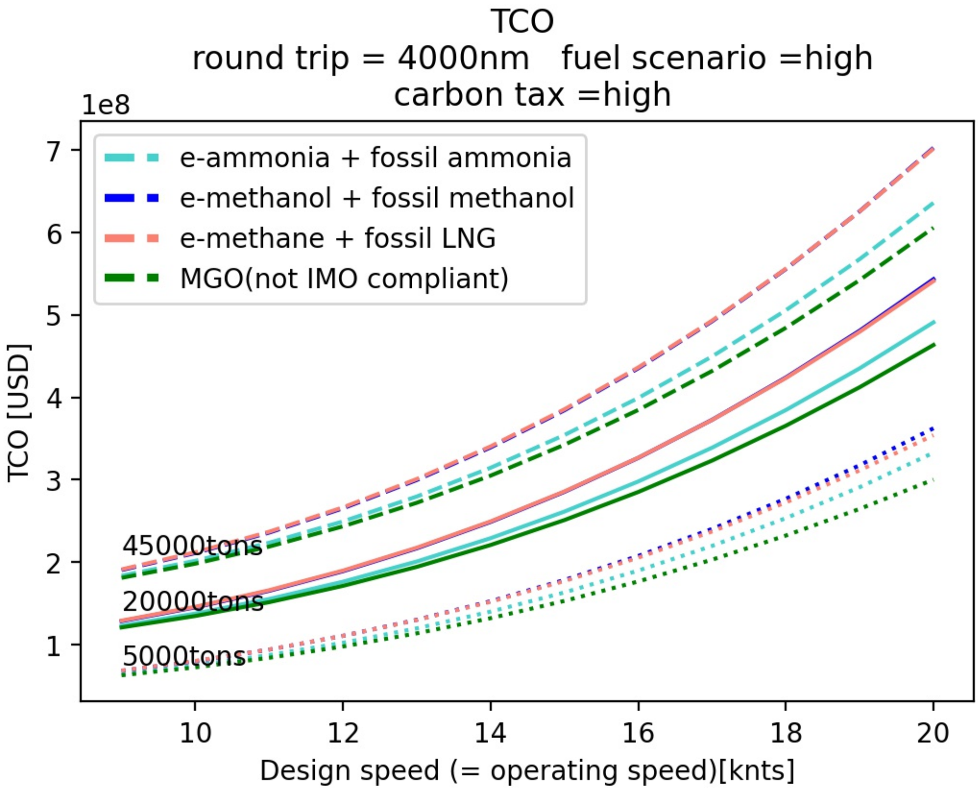

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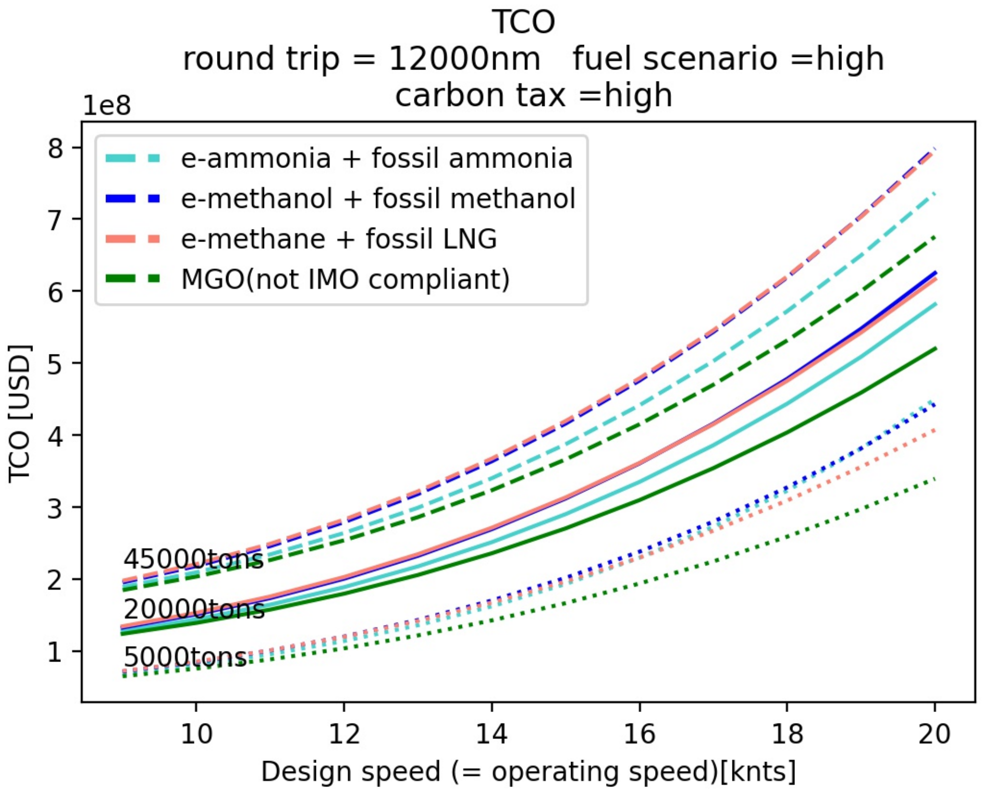

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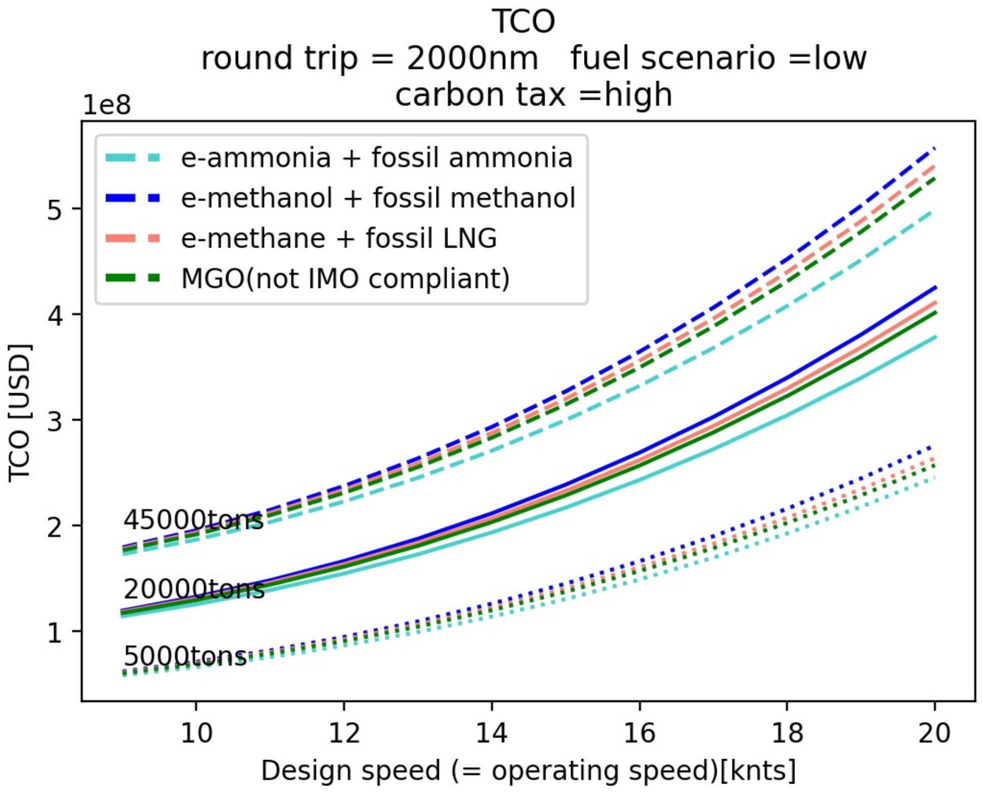

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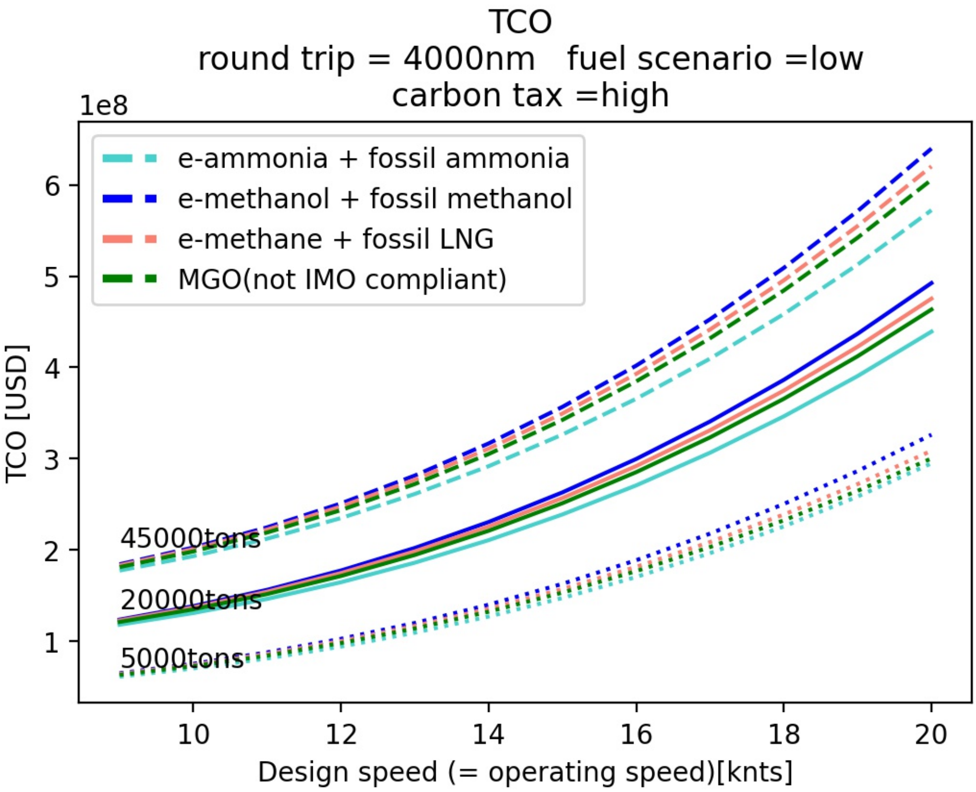


Figure D.17

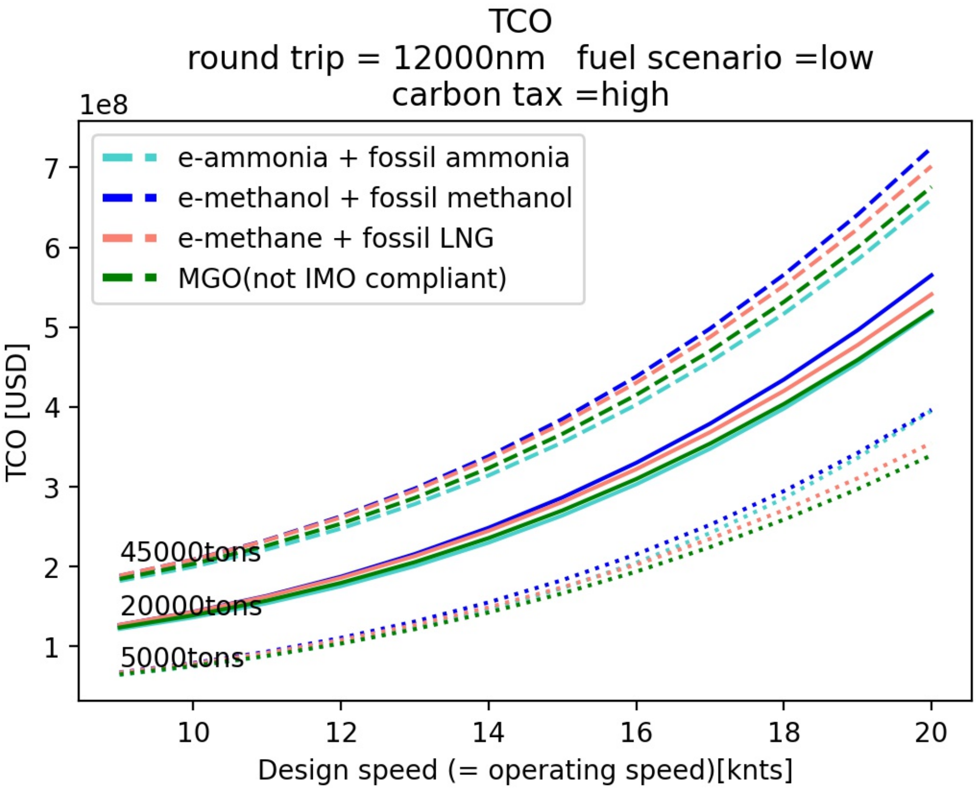


Figure D.18

D.1. Timeline of cumulative TCO of the small, mid and large scale vessel for scenario 12

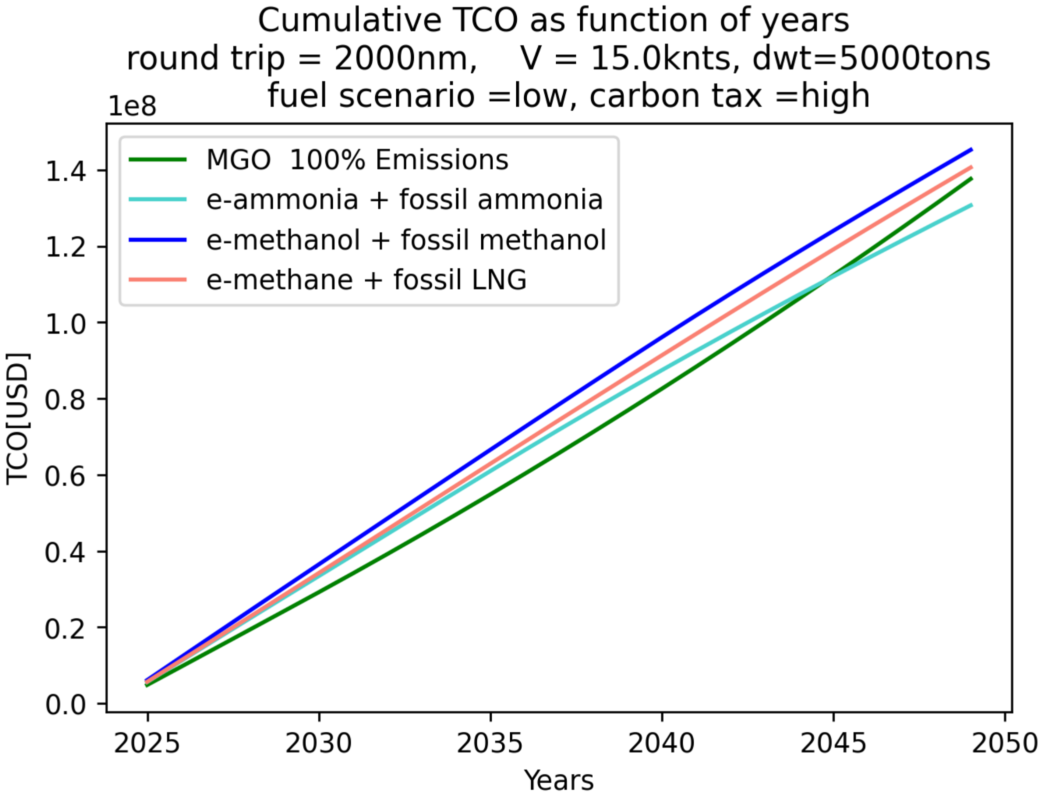


Figure D.19: The figure depicts the breakeven point for the selected fuel for scenario 12 for the small scale tanker. The

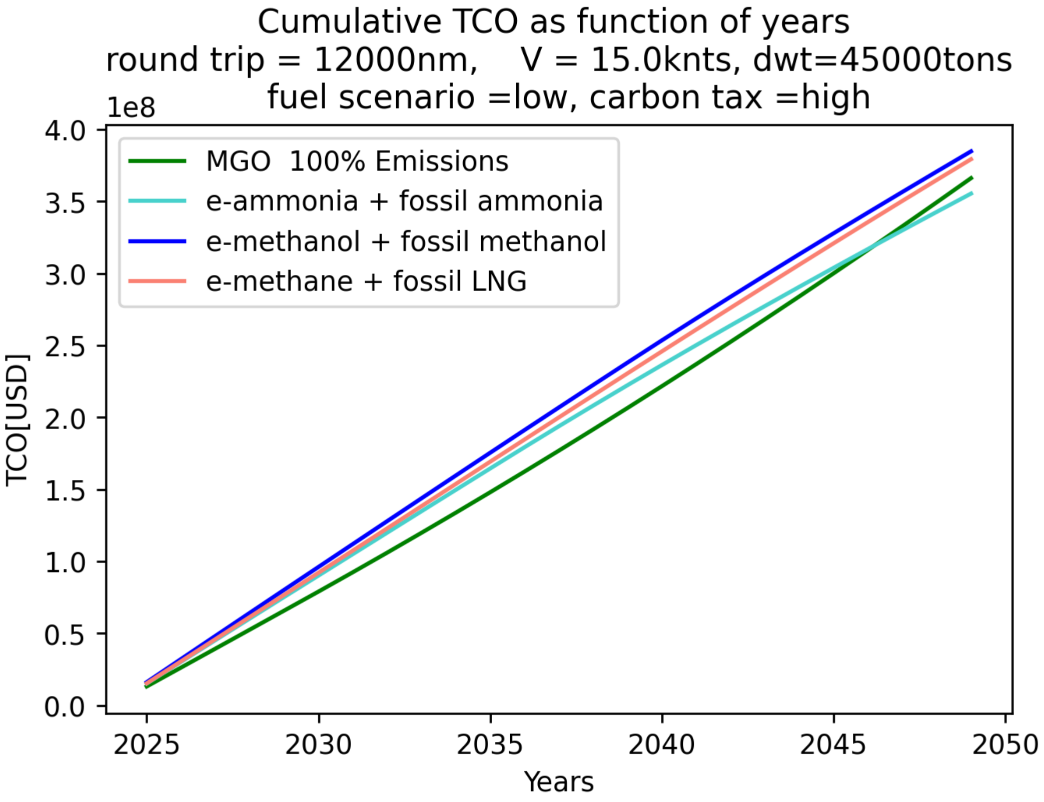
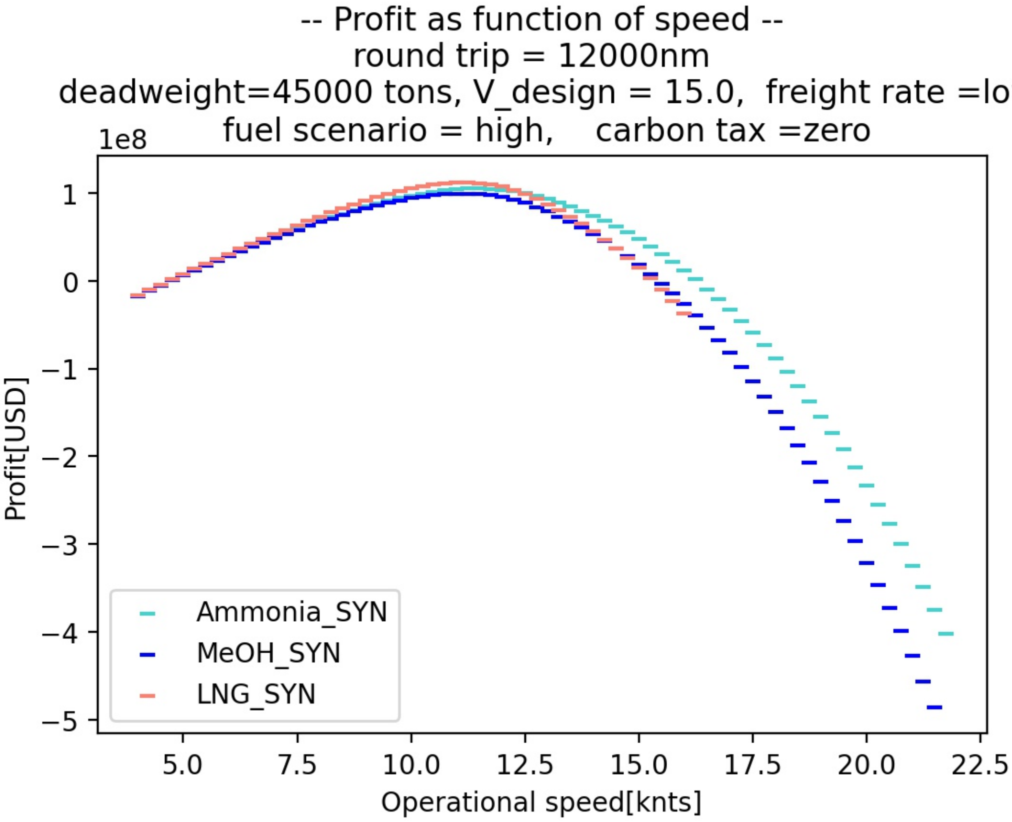


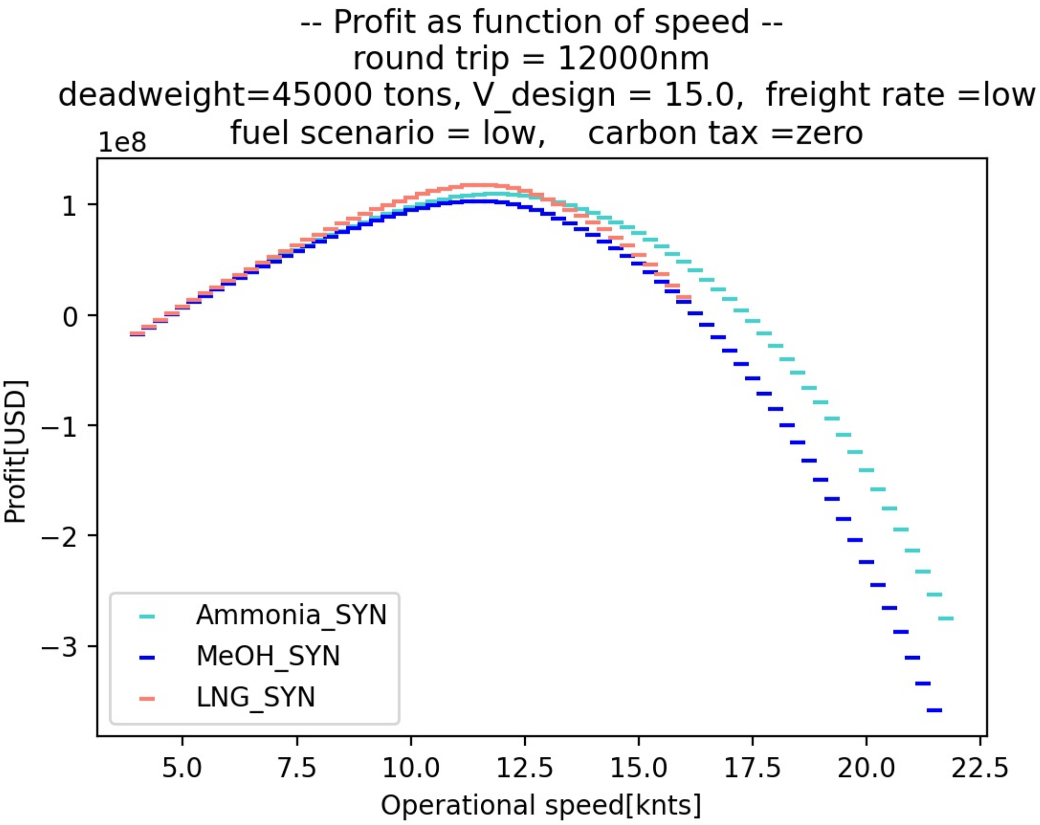
Figure D.20: The figure depicts the breakeven point for the selected fuel for scenario 12 for the large scale tanker. The

E

Complete overview of the results of chapter 9

E.1. Low freight rate

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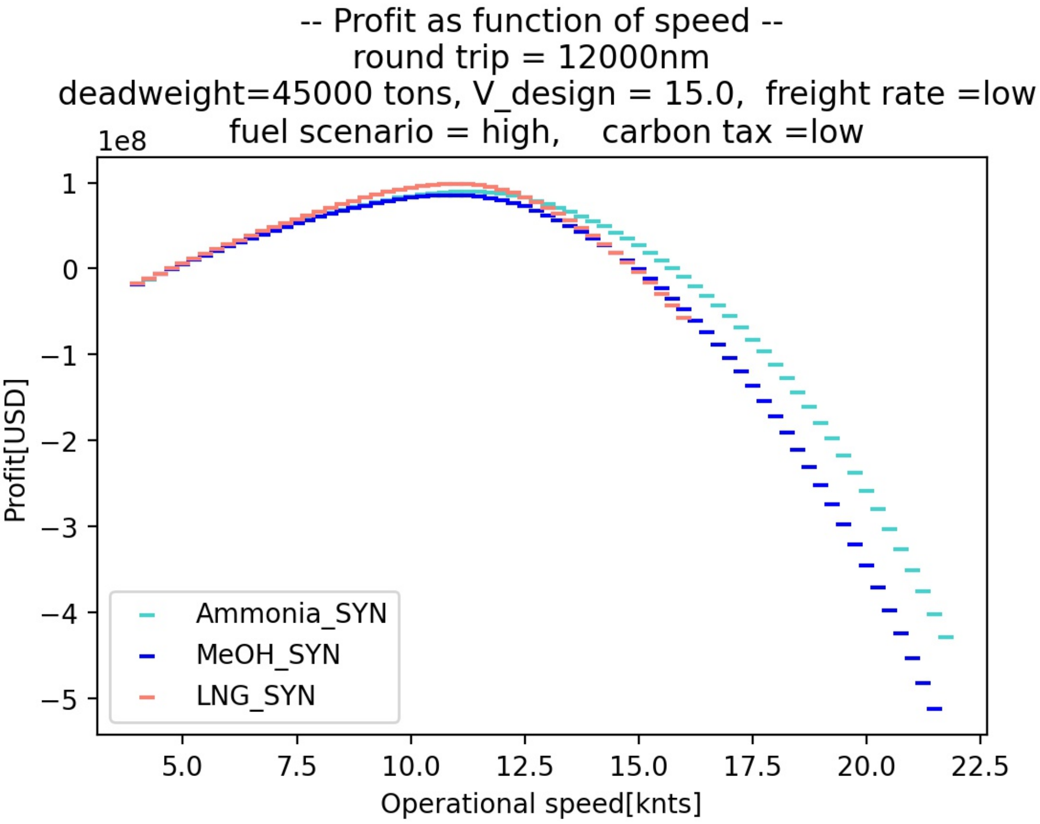
fuel scenario = low, carbon tax =zero
1e8
1
0
−1
−2
−3
Profit[USD]
Ammonia_SYN
MeOH_SYN
LNG_SYN
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]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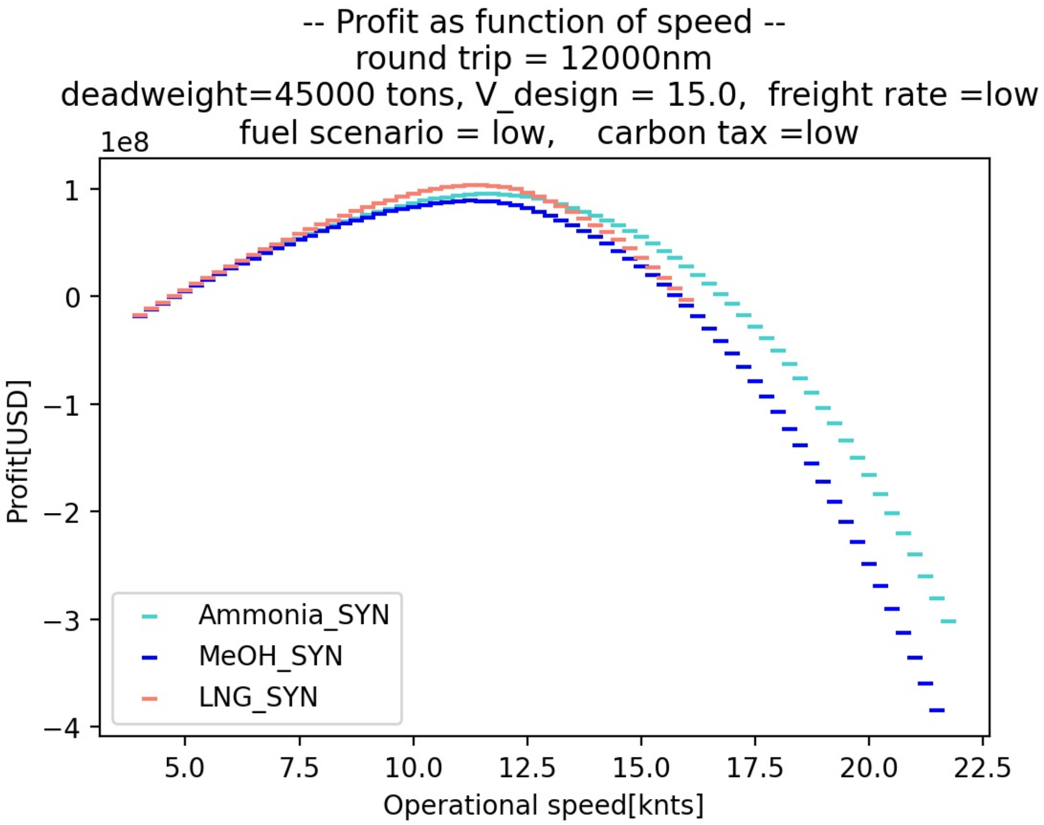
fuel scenario = high, carbon tax =low
1e8
1
0
−1
−2
−3
−4
−5
Profit[USD]
Ammonia_SYN
MeOH_SYN
LNG_SYN
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]


-- Profit as function of speed --
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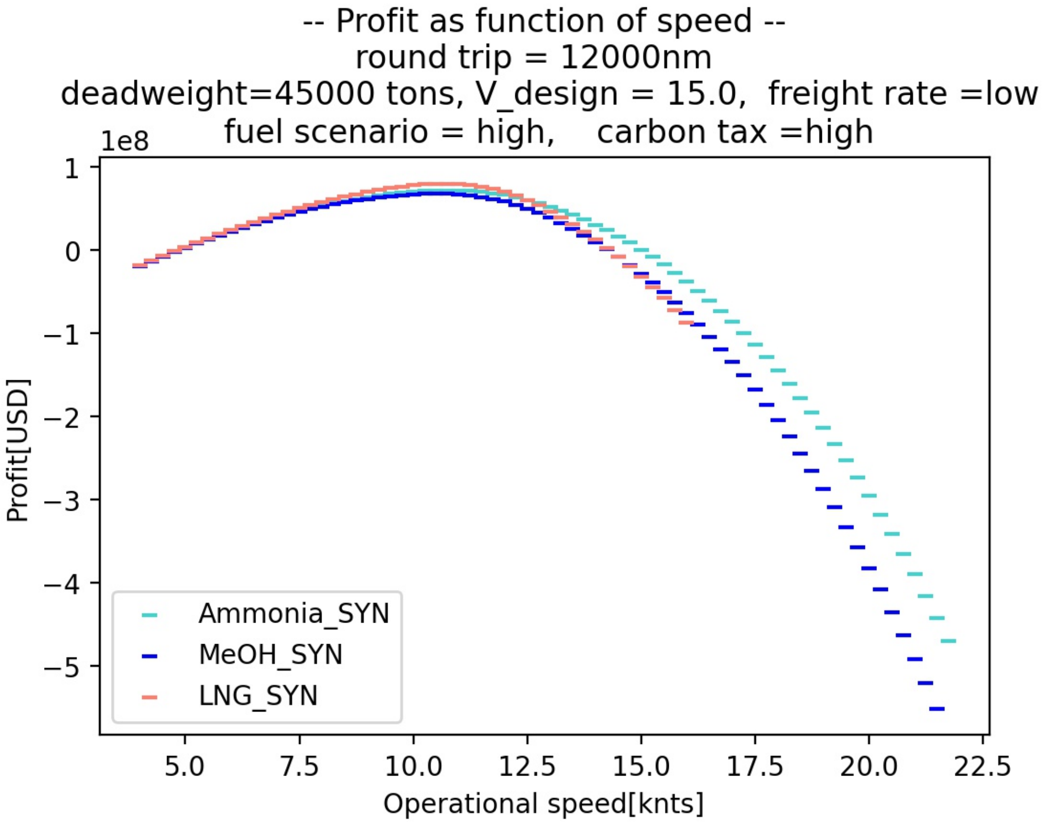
deadweight=45000 tons, V_design = 15.0, freight rate =low
fuel scenario = low, carbon tax =low
1e8
1
0
−1
−2
−3
−4
Profit[USD]
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]
Ammonia_SYN
MeOH_SYN
LNG_SYN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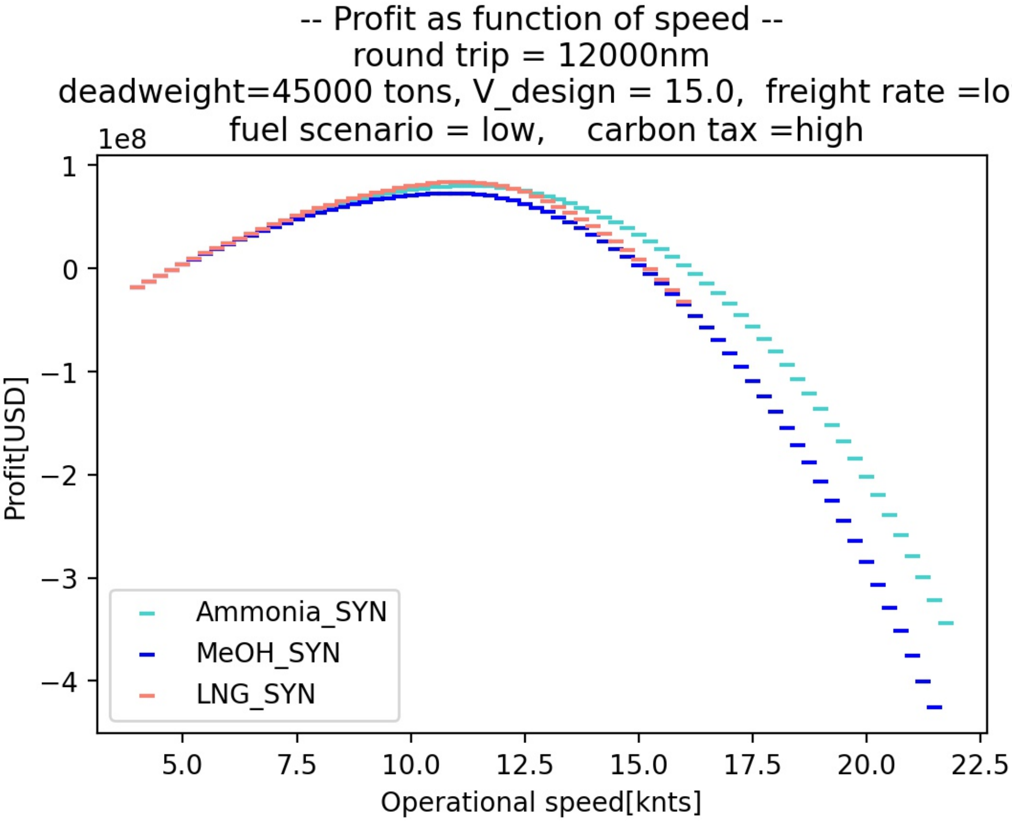
deadweight=45000 tons, V_design = 15.0, freight rate =low
fuel scenario = high, carbon tax =high
1e8
1
0
−1
−2
−3
−4
−5
Profit[USD]
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]
Ammonia_SYN
MeOH_SYN
LNG_SYN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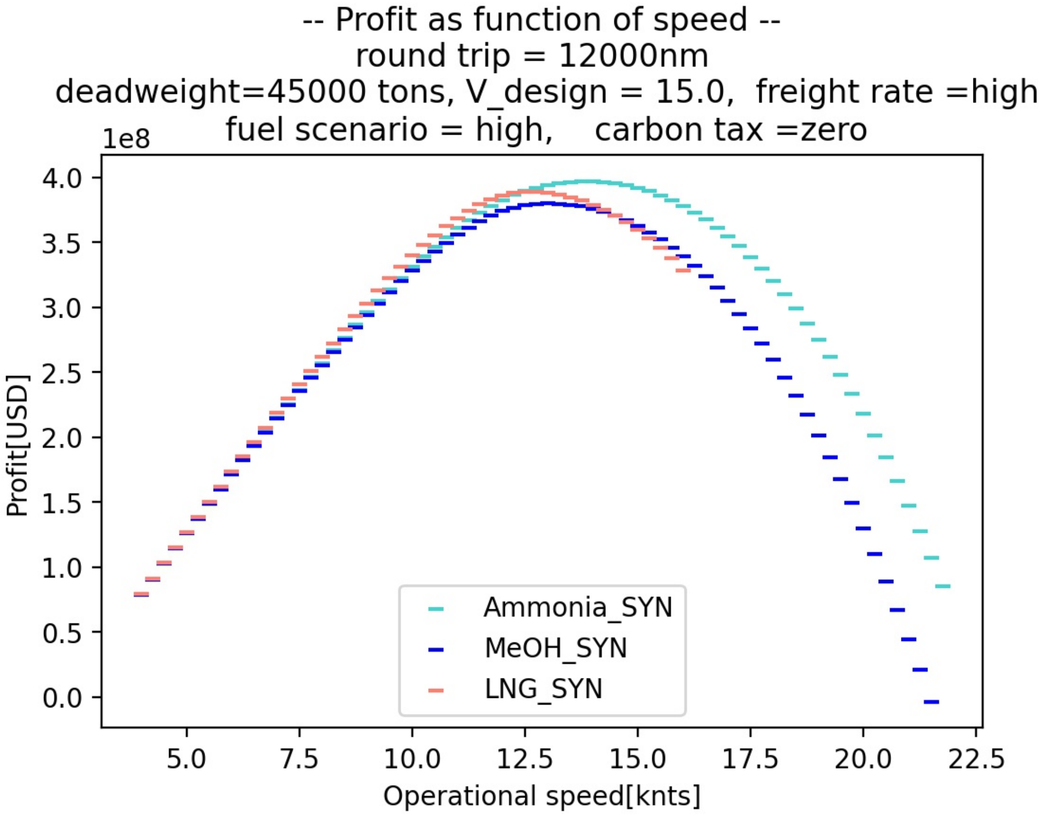
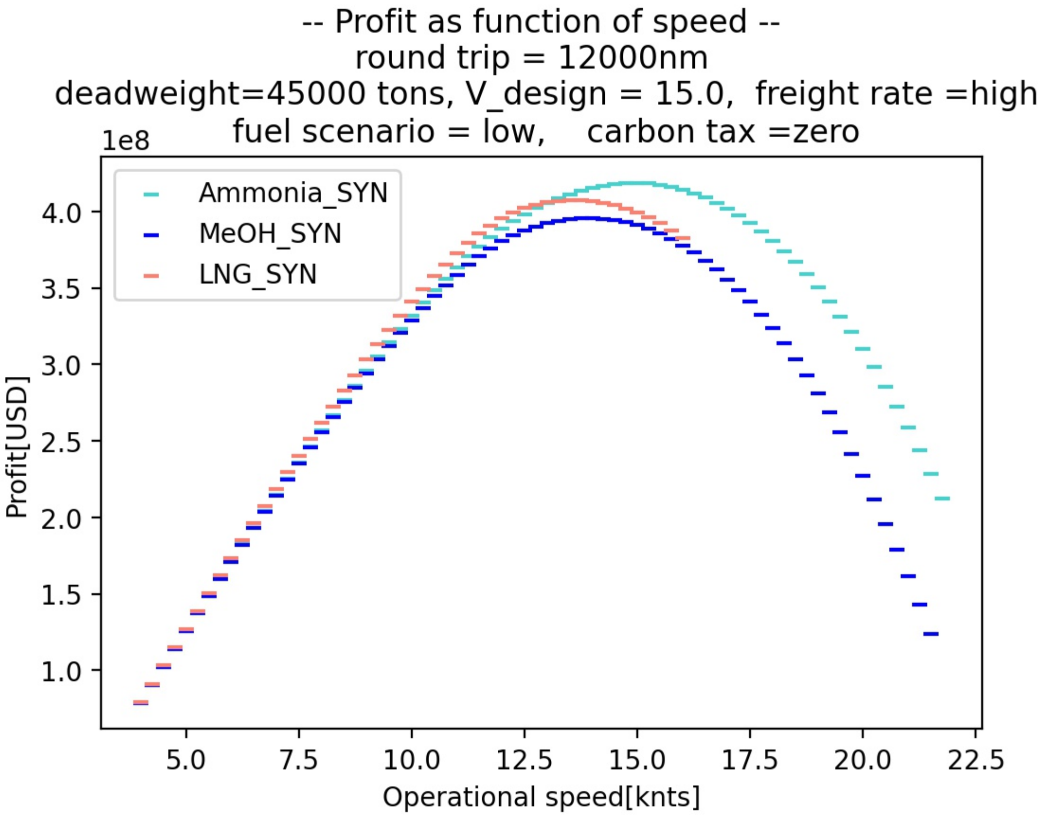
deadweight=45000 tons, V_design = 15.0, freight rate =low
fuel scenario = low, carbon tax =high
1e8
1
0
−1
−2
−3
−4
Profit[USD]
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]
Ammonia_SYN
MeOH_SYN
LNG_SYN

E.2. High freight rate

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Ammonia_SYN
MeOH_SYN
LNG_SYN
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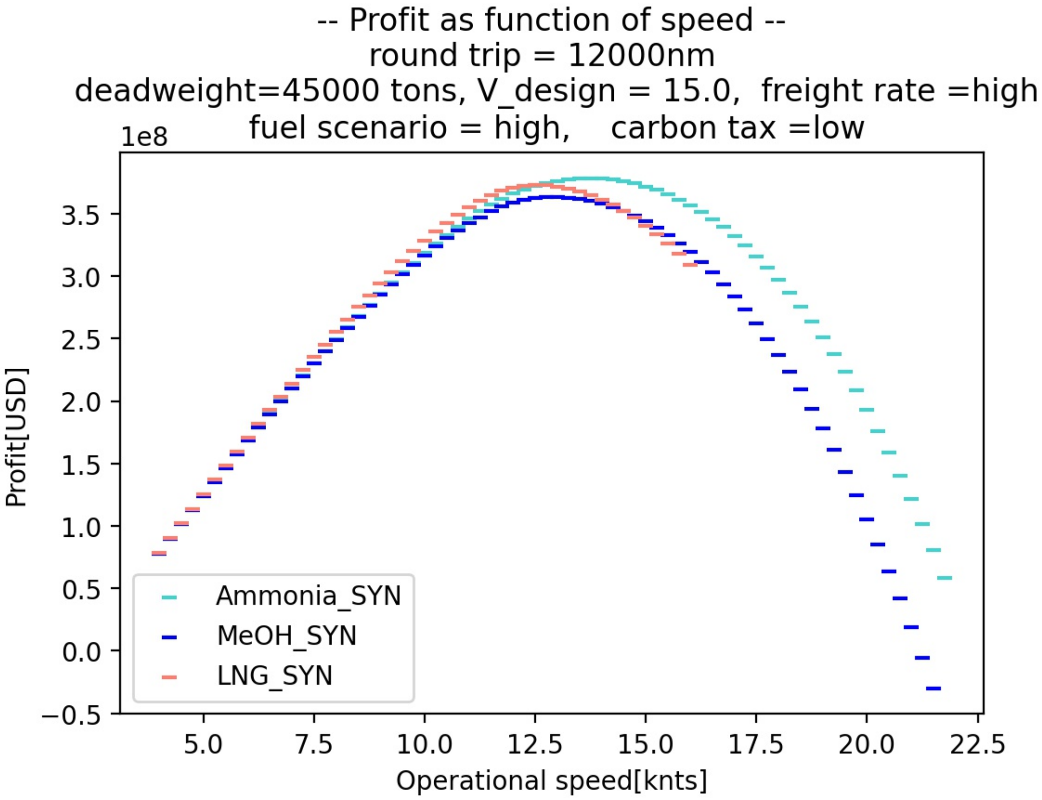
3.5
3.0
2.5
2.0
1.5
1.0
Profit[USD]
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]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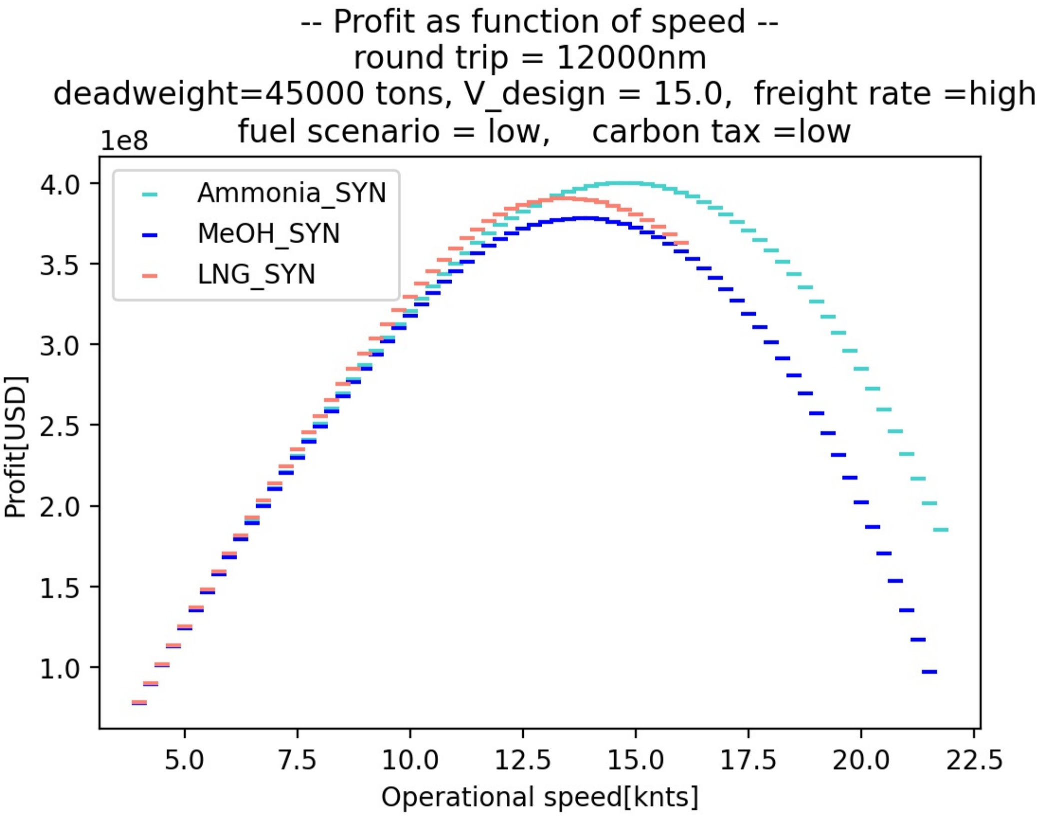
fuel scenario = high, carbon tax =low
1e8
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Profit[USD]
Ammonia_SYN
MeOH_SYN
LNG_SYN
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]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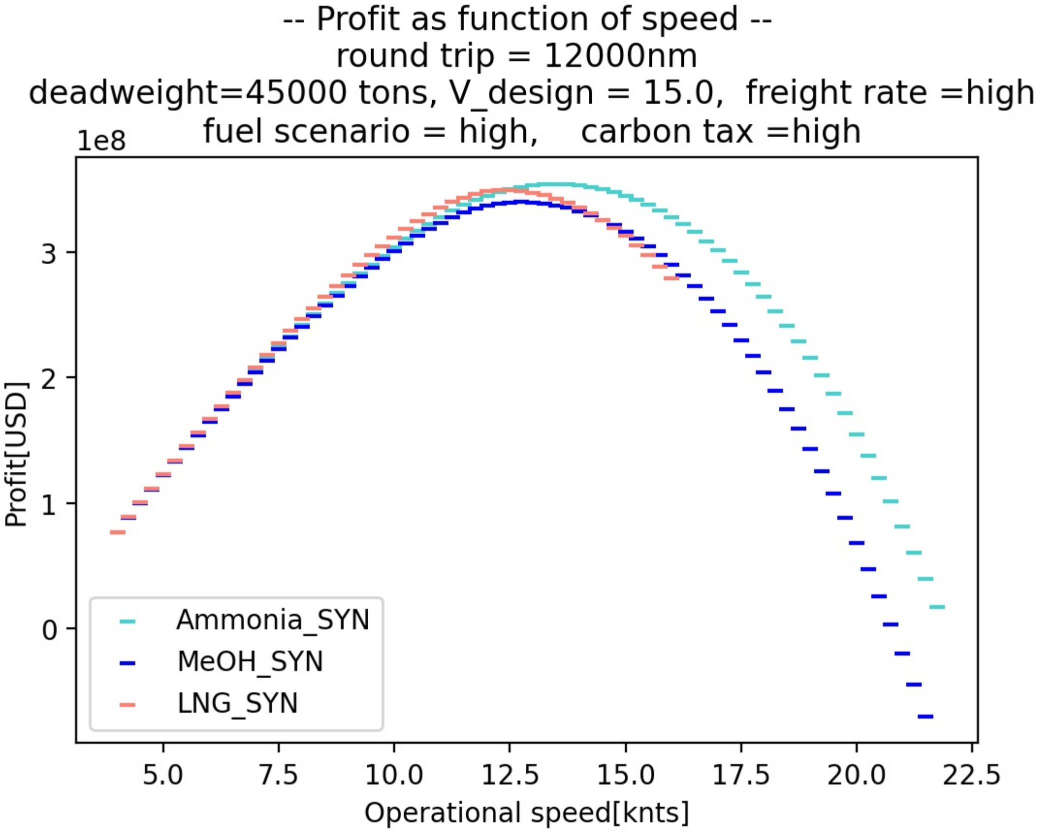
deadweight=45000 tons, V_design = 15.0, freight rate =high
fuel scenario = low, carbon tax =low
1e8
Ammonia_SYN
MeOH_SYN
LNG_SYN
Profit[USD]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]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fuel scenario = high, carbon tax =high
1e8
Ammonia_SYN
MeOH_SYN
LNG_SYN
Profit[USD]
3
2
1
0
5.0
7.5
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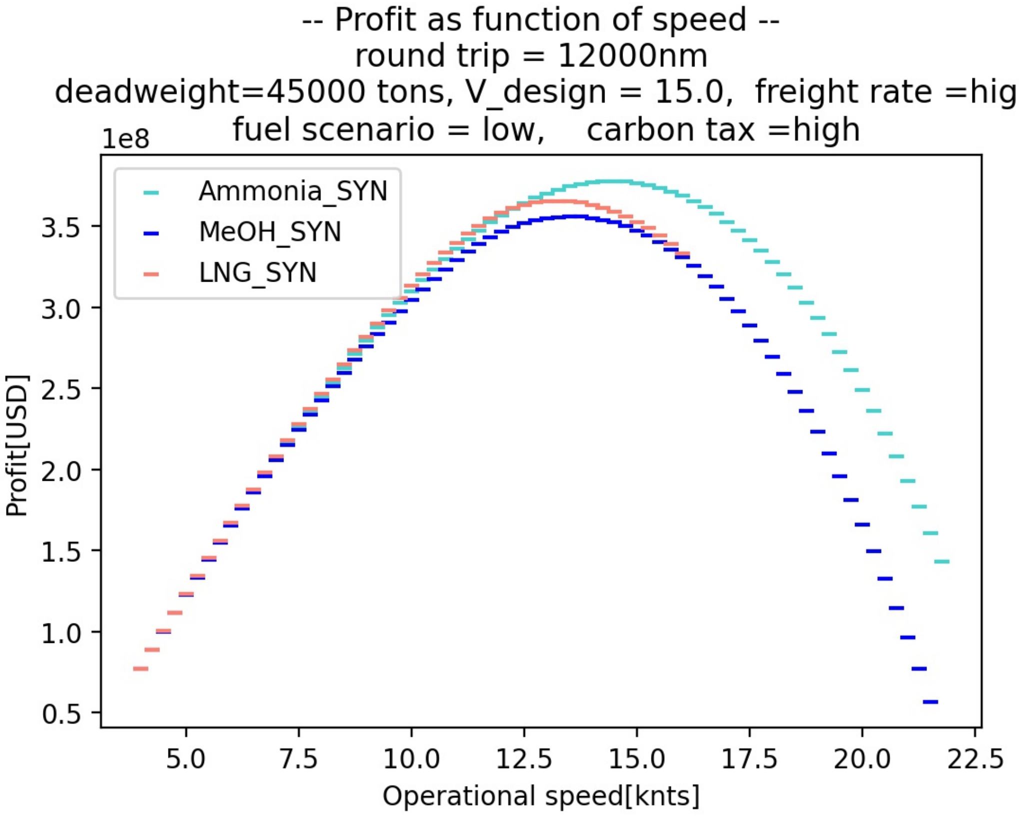
17.5
20.0
22.5
Operational speed[knts]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1e8
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MeOH_SYN
LNG_SYN
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2.5
2.0
1.5
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Profit[USD]
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Operational speed[knts]

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