Decarbonizing EU Maritime Fuel Mix using RFNBOs

A Techno-Economic-Emission Analysis on the effects of FuelEU Maritime Legislation in the EEA Fuel Mix with Special Focus on RFNBOs

Utrecht University

accenture

Friso Meijer (6017711) Supervisor (UU): Prof. Dr. Gert Jan Kramer Supervisor 1 (Accenture): Elaine Kreiken Supervisor 2 (Accenture): Jan Karel van den Biesen Date: 02/01/24

ABSTRACT

The oceanic maritime sector, crucial for global trade, predominantly relies on polluting Heavy Fuel Oils (**HFO**), contributing to approximately 3% of annual GHG emissions. Decarbonizing this sector poses a significant challenge due to its international nature and the substantial technological investments required. The recently adopted FuelEU Maritime (**FEUM**) legislation, as part of the European Green Deal (**EGD**), is a pioneering piece of legislation mandating incremental greenhouse gas (**GHG**) intensity reductions for maritime fuels. Additionally, the law features several instruments to incentivize the uptake of Renewable Fuels of Non-Biological Origin (**RFNBO**), such as e-ammonia (**NH_3**) and e-methanol (**CH_3OH**). FEUM targets the fuel tanks within commercial vessels exceeding 5,000 GT (gross tonnage) voyaging from and to ports within the European Economic Area (**EEA**). Previous research has focused either the effects of FEUM on the container ships category or on global maritime sector decarbonization pathways. This study offers a comprehensive analysis of FEUM's techno-economic and emissions implications on the entire EEA-operating fleet. Through a combination of scenario analysis and cost-minimization modelling from the perspective of shipping companies, fleet size, optimal fuel mix and GHG abatement costs were assessed. Key findings indicate a shift away from liquid towards gaseous fossil fuels and a notable increase in demand for RFNBOs in the late 2030s, particularly NH_3 over CH_3OH. Despite an 80% reduction GHG intensity in 2050, absolute emissions decline marginally due to sector expansion. Total fuel associated costs premiums range between 61-74% by 2050. Geographical RFNBO production location, minimally impact RFNBO demand and costs in the long run. Assessing FEUM's implications serves to gauge the legislation's (cost-)effectiveness in achieving its targets and guides policy recommendations.

SYNOPSIS

This work is divided into seven chapters with each chapter having an introductory paragraph to inform the reader on what is to come. Below follows a quick description of all chapters so as to guide the reader through it as efficiently as possible.

INTRODUCTION: Describes the issue at hand and the societal relevance of finding a solution. Here the gap in literature is identified and based on this, the research aim, and question are given. Additionally, sub-questions are provided accompanied with brief descriptions. Finally, the scientific relevance is outlined.

THEORETICAL BACKGROUND: Extensively covers FEUM legislative document, RFNBOs and publications by the MarE-fuel research group, as this work primarily builds on this literature. Other literature served for research/model design, data procurement and to provide readers with a comprehensive understanding of all concepts used in later chapters. Cross-referenced hyperlinks are included to guide the reader to the relevant sections. Readers that are familiar with the maritime industry may opt to skim this part, although it provides relevant context for this research.

METHODOLOGY: Outlines and justifies the methodology employed in this research. The methodology can be categorized in three parts: Research/model design (**3.1-3.2**), data procurement (**3.3**-Error! Reference source not found.) and outcome interpretation (**3.5**).

RESULTS: Are structured per sub question outlined in the introduction and are linked back to the theoretical background using cross-referenced hyperlinks. Findings start general and gradually become more specific. This is essentially the reason why FEUM has been adopted, as explained in **Section 2.1.1.**

CONCLUSION: Provides a short summary of this work and answers the main research question.

POLICY RECOMMENDATIONS: Describes the recommendations for FEUM adaption following the results of this research, aiming to inform future legislative decision.

DISCUSSION: Lists the limitations of perceived significance to provide a critical analysis of the findings. Finally, the theoretical implications of this research are discussed, providing avenues for further research.

NOMENCLATURE

AE	Alkaline Electrolysis
AFIR	Alternative Fuels Infrastructure Regulation
BDN	Bunker Delivery Notes
BECCU	Bio-Energy Carbon Capture Utility
BHM	Behind the Meter
C	Carbon
C3H8	Propane
C4H10	Butane
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture Utility
CH3OH	Methanol
CH4	Methane
CMS	Carbon Molecular Sieves
CO	Carbon Monixide
CO2	Carbon Dioxide
CO2eq	GHG emissions in CO2 equivalent
COx	Carbon Oxides
CRF	Capital Recovery Factor
DAC	Direct Air Capture
DF	Dual Fuel
DME	Dimethyl Ether
DTU	Technical University of Denmark
ECA	Emission Control Areas
ECL	European Climate Law
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EGD	European Green Deal
ETS	Emissions Trading System
EU	European Union
FEUM	FuelEU Maritime
FF	Fossil Fuel
G	Giga (10^9)
g	Gram
GHG	Greenhouse Gas
GJ	Gigajoules
GT	Gross Tonnage
gt	Gigatonne
H2	Hydrogen
H20	Water
HB	Haber-Bosch
HFO	Heavy Fuel Oils
AE	Alkaline Electrolysis
HHV	Higher Heating Value
ICE	Internal Combustion Engine
IEA	Intranational Energy Agency
IEA	Intranational Energy Agency
IMO	Intranational Maritime Organization
IPCC	Intragovernmental Panel for Climate Change
J	Joule
k	Kilo (10^3)
LBG	Liquified Bio Gas
LCOE	Levelized Cost of Electricity
LCV	Lower Calorific Value
LHV	Lower Heating Value
LNG	Liquified Natural Gas
LPG	Liquified Petrol Gas
M	Mega (10^6)
MDO	Marine Diesel Oil
ME-C	Mechanical Engine - Carbon
ME-GI	Mechanical Engine - Gas injected
ME-LGIa	Mechanical Engine - Liquid Gas Injected ammonia
ME-LGIm	Mechanical Engine - Liquid Gas Injected methanol
ME-LGIp	Mechanical Engine - Liquid Gas Injected propane
MGO	Marine Gas Oil
MRV	Monitoring, Reporting, Verification (database)
MTBE	Methyl tertbutyl ether
N2	Nitrogen
NH3	Ammonia
NM	Nautical Mile
NOx	Nitrogen Oxides
NZE	Net Zero Emission
O&M	Operational & Maintanance (costs)
O2	Oxygen
OF	Objective Function
OPEX	Operational Expenditures
P	Peta (10^15)
p.p.	percent point
PEME	Proton Exchange Membrane Electrolysis
PM	Particulate Matter
PO	Pyrolysis Oil
PSA	Pressure Swing Adsorption
PtF	Power to Fuel
RCP	Representative Concentration Patways
RED	Renewable Energy Directive
RES	Renewable Energy Systems
HHV	Higher Heating Value
RFNBO	Renewable Fuels of Non-Biological Origin
RPM	Revolutions Per Minute
RR	Ramping Rate
SF	Single Fuel
SFC	Specific Fuel Consumption
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SOEC	Solid Oxide Electrolysis Cell
SOx	Sulfur Oxides
SOx	Sulfur Oxides
SOx	Sulfur Oxides
SSE	Shoreside Electricity
SSP	Socioeconomic Pathways
t	Tonne
TCO	Total Cost of Ownership
TFC	Total Final Consumption
TLR	Technology Readiness Level
TtW	Tank-to-Wake
UNCTAD	United Nations Conference on Trade and Development
VLSFO	Very Low Sulfur Fuel Oil
W	Watt
WGS	Water Gas Shift
wt%	Weight percentage
WtT	Well-to-Tank
WtW	Well-to-Wake

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1. INTRODUCTION

Externalities of human activities are significantly impacting the stability and resilience of ecosystems worldwide. Global temperature rise is now almost unanimously accepted to be largely caused by a steady increase in atmospheric greenhouse gases (**GHG**) since the industrial revolution [1]. With approximately 75% of the warming potential, carbon dioxide (**CO_2**) is by far the GHG with the largest contribution to this problem [2]. If unaddressed, global warming will give rise to a wide array of negative ecological outcomes such as loss of biodiversity, oceanic acidification and increased likelihood and gravity of extreme weather events [3]. These ecological shifts, otherwise known as the climate crisis, not only put strain on natural systems but also pose a real threat to societies and, as some believe, even to human survival [4].

In 2015, the Paris Agreement established a legal framework to strengthen the global response to this problem. The main stated objective was that global warming must be kept well below two degrees Celsius above pre-industrial levels [5]. Seven years later, the Intergovernmental Panel for Climate Change (**IPCC**) alarmingly estimates in its 2023 report that the global average surface temperature increase currently sits between 0.8°C and 1.3°C with a best estimate of 1.07°C [1].

Despite a brief decline in GHG emissions during the covid pandemic, 2022 gave rise to a new record of 36.8 Gt CO_2 [6]. It is estimated that if current trajectories continue, the remaining carbon budget for staying within 2°C will be spent before 2045 with a likelihood of 67% [7]. Such findings underscore the urgency for rapid and decisive transitioning towards a sustainable system.

Responsible for roughly 2/3rds of the global GHG emissions, the energy sector is the main culprit to the climate crisis and should therefore be at the heart of the solution [8]. The Intranational Energy Agency (**IEA**) estimates in their 2023 flagship report that ‘conventional’ abatement methods such as improved energy efficiency, electrification, Renewable Energy Systems (**RES**) and behavioral change will account for over 70% of GHG reduction in the Net Zero Emission (**NZE**) pathway [9]. However, the largest challenge in solving the energy sector’s impact on atmospheric GHG concentration is the decarbonization of industries which rely heavily on fossil fuels for high-temperature processes or chemical feedstocks [10]. These industries cannot be electrified and among them are some of the most critical industries in modern society, such as iron and steel, cement, chemicals, and long-distance transport. These sectors are known as the ‘hard-to-abate sectors’ and require different solutions such as process integration and alternative fuels [11].

One of these sectors is ocean shipping, which most industries rely on greatly as part of their supply chain [12]. This is because supply chains are global and ocean shipping is the most cost-effective mode of bulk transport. As a result, an overwhelming 80 percent of goods are transported via ships, making it the backbone of international trade. Between 1990 and 2021, the volume of cargo transported by ships nearly tripled and from 2013 and 2021, the carrying capacity of the global merchant fleet increased by 43%. Several studies expect this rate of growth to accelerate further over the next thirty years as a result of population increase and urbanization in Africa, Asia, and South America [13] [14].

The engines of the global merchant fleet are for the largest part powered by Heavy Fuel Oil (**HFO**), a low-value byproduct of fossil fuel refineries [15] [16]. This cheap fuel is associated with a multitude of environmental impacts which remain largely unregulated [17]. In 2018 the merchant fleet emitted $1.08GtCO_{2eq}$, (billion tonnes) equivalent to roughly 3% of the annual total atmospheric GHG emissions [18]. If unregulated, the International Maritime Organization (**IMO**) estimates that emissions would increase by 90 – 130% between 2020 and 2050 [19]. Ocean shipping is therefore a key obstacle in the path of making supply chains truly green.

In essence, the true challenge lies in the global nature of the maritime sector. Ships depart from one jurisdiction and arrive in another, while spending most of the time in between in international waters. This limits the tools countries can employ to mandate lower GHG emissions [20]. Even if individual nations were to impose stringent emission regulations, they face the risk of ships strategically avoiding their ports and opting for neighboring ones. In addition, achieving decarbonization of ships requires substantial technological shifts and widespread adaptation of alternative low and zero carbon fuels. This demands significant investments to build new fuel supply chains, redesign ships, adapt engine technology and improve operational efficiency. These interventions will drive up costs for shipowners, industry, and final consumers. They could prove too big for individual countries to shoulder.

Luckily, the European Union (**EU**) spearheads the decarbonization efforts via the European Green Deal (**EGD**), which aims to reduce member states' net greenhouse gas emissions by at least 55% by 2030 (Fitfor55) and become the world's first climate neutral continent by 2050 [21]. Besides setting climate targets, the EGD sets a precedent on how to reach them [22]. The targets of the EGD are legally binding for EU member states as they have been written into law under the European Climate Law (**ECL**) [23].

On July 25, 2023, the EU adopted the FuelEU Maritime (**FEUM**) initiative as part of the EGD. This first of its kind legislation mandates shipping companies to reduce the emissions of the fuels used in commercial vessels exceeding 5,000 GT (gross tonnage) that voyage to and from EEA ports [24]. **Figure 1** illustrates the law's progressive reduction targets, starting with a 2% cut in 2025 and increasing to an ambitious 80% in 2050.

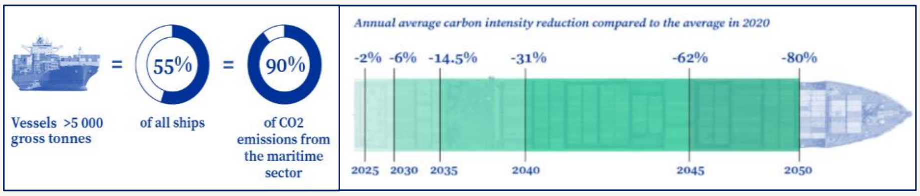

Figure 1: Overview of the targeted fleet and the annual GHG intensity reduction it is mandated to achieve compared to 2020 [25]

The FEUM legislation goes beyond reduction targets by featuring several instruments which incentivize the uptake of a category of desired alternative fuels called Renewable Fuels of Non-Biological Origin (**RFNBO**). Also known as e-fuels, these alternatives, including green hydrogen (**H_2**) and hydrogen derivatives such as green ammonia (**NH_3**) and green methanol (**CH_3OH**) require no biological feedstocks in their production processes and can be fully carbon neutral [26].

The preference for RFNBOs was anticipated by maritime industry leaders, as indicated in **Figure 2**, depicting the outcome of a 2022 market survey by Shell and Deloitte [27]. In this survey, industry leaders expected NH_3 and CH_3OH to feature prominently in the future fuel mix [28]. 2023 saw methanol powered ships go mainstream with 138 orders, surpassing LNG orders [29]. The year also market the breakout year for ammonia, with 11 vessels ordered and more in the pipeline, underscoring that a megatrend might have started in the maritime industry [30].

2022	Pyrolysis Oil	LNG	Methanol	Ammonia	Electric
Part of fuel mix (% participants indicating yes)					

Figure 2: Shipping experts' outlook on alternative fuels. [28]

The price of renewable hydrogen, which is the precursor for any RFNBO, varies significantly based on the production location due to varying renewable energy potentials. The EU expects its demand will far outpace its own production capacity and has therefore set a target for 10Mt (million tonnes) of annual domestic hydrogen production and 10Mt of annual imports by 2030 . A portion of which is earmarked for use in the maritime industry.

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The maritime fuel mix is a product of a complex interplay of technoeconomic and environmental factors such as fuel price, shipping demand, infrastructure maturity, technological readiness, and regulatory compliance. Shipping companies, mandated to adhere to FEUM legislation, face the test of minimizing costs while ensuring compliance. While the regulatory framework for FEUM legislation is clear, the full extent of its techno-economic and emissions implications of it remain to be assessed. A review of literature reveals that only T&E, Europe's leading clean transport campaign group, have modelled the implications of FEUM [31]. However, the scope used was restricted to the container shipping market and as will become clear from **Section 4.1.1**, the container shipping market served a mere 23% of all shipping demand in 2020. Additionally, one cannot extrapolate findings on to the entire EEA market due to vastly different characteristics compared to other shipping categories. This clear gap in research is the focus of this dissertation.

Therefore, the aim of this research is to assess the impact of FEUM by first modelling the future fuel mix under various scenarios from the perspective of the share of the maritime industry which is mandated to adhere to FEUM. Then the cost-effectiveness of reducing GHG emissions per scenario is assessed as well as the resulting increase in fuel related costs. To achieve these objectives, the following research question has been devised:

Research Question: What are the techno-economic and emission implications of FuelEU Maritime legislation?

To comprehensively answer the overarching research question, a set of sub-questions has been formulated. These are mutually exclusive, focusing on separate elements of the main question without redundancy, and collectively exhaustive, ensuring that they together provide a comprehensive answer to the main research question.

Sub question 1	What are the expected changes in the size and composition of the EEA-operating maritime fleet from 2020 until 2050?
Sub question 2	What is the optimal fuel mix for shipping companies to meet FuelEU Maritime targets per shared socioeconomic pathway and RFNBO production location?
Sub question 3	What is the cost-effectiveness of abating GHG emissions per shared socio-economic pathway and RFNBO production location?
Sub question 4	How do outcomes change as specific input values change?

Assessing the FEUM legislation's implications serves both scientific and societal purposes. It gauges the legislation's effectiveness in reducing the maritime fuel mix's GHG intensity, potentially soliciting adaptations. In addition, this research assesses the demand for RFNBOs within the 'must conform' part of the maritime sector and examines the price tag associated. The outcomes could be used as data for debate on government spending and profit margin redistribution. Finally, this study may stimulate further research into, for instance, the impact of FEUM on the competitiveness of European-produced goods.

2. THEORETICAL BACKGROUND

To provide the reader with a thorough understanding of all topics involved in answering the main research question and its related sub-questions, this section covers the theoretical background of the regulatory measures of FEUM legislation, RFNBO definitions and criteria, the MarE-fuel publications and the SEAMPAS minimization model, Power-to-Fuel production pathways, marine fuel characteristics, the MRV database and scenario thinking.

2.1 FUEL EU MARITIME LEGISLATION

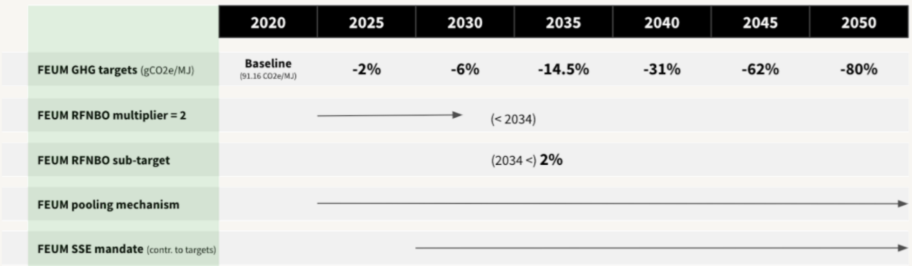
This chapter discusses the intended workings of the FEUM, its scope, the instruments and how shipping companies can comply with it. The information and data used in this chapter are derived from the official FuelEU legislative document and an explainer by 'Transport & Environment' [24] [32]

2.1.1 Overview

The FuelEU Maritime (**FEUM**) initiative is the latest EU regulation that is aimed at reducing the GHG intensity of maritime fuels. It was adopted by the European Council on 25 July 2023 and is a part of the overarching "Fit for 55" package, which serves to reduce the continent's GHG emissions by 55% by 2030. Alongside the newly adopted FEUM legislation, there exist other EU schemes to jumpstart the shipping's fuel transition like the Emissions Trading System (**ETS**), the Renewable Energy Directive (**RED**) and the Alternative Fuels Infrastructure Regulation (**AFIR**). These pieces of legislation allow shipping companies to trade carbon credits, increase the supply of low-carbon fuels and set mandatory targets for electric charging and hydrogen refueling infrastructure. However, by themselves they will not be enough to drive the uptake of low-carbon fuels, hence the need for additional legislation. As a response FEUM was introduced. This additional legislative instrument sets accelerates the fuel transition by:

- → Progressively reducing GHG intensity of the fuel used in ship propulsion from 2025 onwards; **[GHG targets]**
- → Stimulating the uptake by introducing a 2x multiplier for RFNBOs until 2034; **[RFNBO multiplier]**
- → Mandating the sector to use at least 2% RNFBOs in 2034 if a sub target of 1% uptake of RFNBOs was not achieved in 2031 by market forces alone; **[RFNBO sub target]**
- → Allowing shipping companies to pool their emissions as well as trade between shipping companies to stimulate economic gain for first movers; **[Pooling mechanism]**
- → Requiring container and cruise ships to connect to shore-side electricity when at berth in EEA ports; **[Shoreside electricity]**

Figure 3 shows a chronological overview of the regulatory measures under FEUM.



	2020	2025	2030	2035	2040	2045	2050
FEUM GHG targets (gCO2e/MJ)	**Baseline** (91.16 CO2e/MJ)	**-2%**	**-6%**	**-14.5%**	**-31%**	**-62%**	**-80%**
FEUM RFNBO multiplier = 2		→	(< 2034)				
FEUM RFNBO sub-target			(2034 <) **2%**				
FEUM pooling mechanism		→					
FEUM SSE mandate (contr. to targets)			→				

Figure 3: A chronological overview of the regulatory measures implemented under the FuelEU legislation. [31]

2.1.2 Scope

In the context of FEUM a ‘voyage’ is defined as any commercial transportation of goods or passengers by sea. FEUM applies to commercial vessels of 5,000 GT (gross tonnage) and above. Fishing boats, offshore service vessels, military ships and private yachts that exceed this capacity threshold are exempt. Irregardless of the flag flown, FEUM targets the 100% of fuel consumed during voyages between the ports of the European Economic Area (EEA) and 50% of the fuel used during voyages between EEA and non-EEA ports (termed ‘third-party ports’ in legislative documents).

In an attempt to discourage circumvention, FEUM has an extended scope. The law treats any port within 300 nautical miles of an EEA port as an EEA port if at least 65% of a ship’s cargo is transshipped here. Transshipping is the process of transferring cargo from one ship to another as part of a longer voyage. It takes place at intermediate ports begore cargo reaches its final destination.

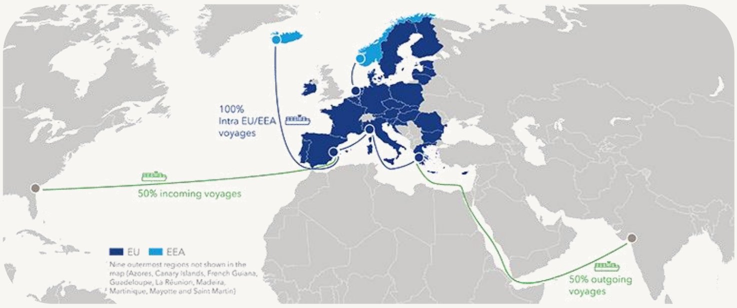


Figure 4: FuelEU Maritime requirements based on percentage of energy used on voyages. [31]

2.1.3 Regulatory measures

2.1.3.1 FEUM GHG Targets

The primary objective of FEUM is to reduce the cabon intesnisty of the maritime fuel mix. Carbon intensity is a measure of how ‘clean’ a process is and is expressed in emissions per unit of energy. While it can be measured in various ways, FEUM mandates the use of Well-to-Wake (**WtW**) measurement as the standard. This method includes the lifecycle GHG intensity of marine fuels in its entirety and ensures that all emissions for production, processing, transportation, and consumption of the fuel are accounted for. This way, FEUM prevents shipping companies from opting for fuels which have lower emissions when measured at a ship’s tailpipe, while contributing to higher emissions upstream. **Figure 5** presents a diagram illustrating the concept of WtW emissions which is a summation of Well-to-tank (**WtT**) emissions and Tank-to-Wake (**TtW**) emissions. WtT emissions represent the upstream process of materials extraction (e.g., oil, natural gas & rare metals), plant construction, and operation. TtW emissions represent emissions that are formed during the operational phase i.e., during fuel combustion.

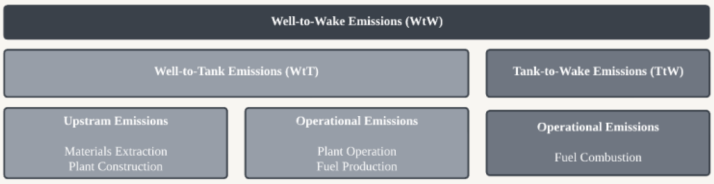


Figure 5: Overview of elements in well-to-wake GHG emissions. [33]

Besides CO_2, fossil fuel combustion emits various other GHG gasses such as CH_4 and N_2O, which have varying global warming potentials (**GWP**) compared to CO_2. A consolidation of the diverse GHG gasses into a unified metric expresses the total warming effect of all GHGs in terms of the equivalent amount of CO_2. The equation is given in equation [1] ^{34}.

$$CO_{2eq,TtW} = (C_{f\ CO_2} \times GWP_{CO_2} + C_{f\ CH_4} \times GWP_{CH_4} + C_{f\ N_2O} \times GWP_{N_2O})_i \qquad [1]$$

Here, the ***CO₂*** equivalent ***TtW*** emissions are calculated as the sum of the products of the carbon fraction (***C_f***), representing the mass of GHG emitted per unit of fuel, of each GHG and their respective GWP.

A simplified equation for calculating TtW and WtT emissions are shown in equation [2]. The more detailed version can be found in **Annex A** ^{34}.

$$CO_{2eq,WtW} = CO_{2eq,WtT} + CO_{2eq,TtW} \qquad [2]$$

The reductions illustrated in Figure 6 are based on the baseline GHG intensity of the 2020 maritime sector voyaging from and to EEA harbors. This WtW baseline is 91.16 gCO_2e/MJ. FEUM mandates that the reduction targets are to be met using fuel switching alone, so that energy efficiency technologies or operational strategies (such as speed reduction) do not count towards meeting the targets.

Figure 6 shows the maximum allowed GHG intensity per year under FEUM, in combination with the default values of WtW GHG intensities per fuel. This value determines the eligibility timeline of individual unmixed fuels. In essence, any fuel with a WtW intensity that sits below the reduction target of year y is eligible for fueling marine vessels in that year. This means that under FEUM liquified natural gas (LNG) could be used as a fuel in certain engines until 2039 despite being a fossil fuel. Bio-LNG would be a suitable fuel until 2049. More on marine engine technology is written in **Section 2.6.**

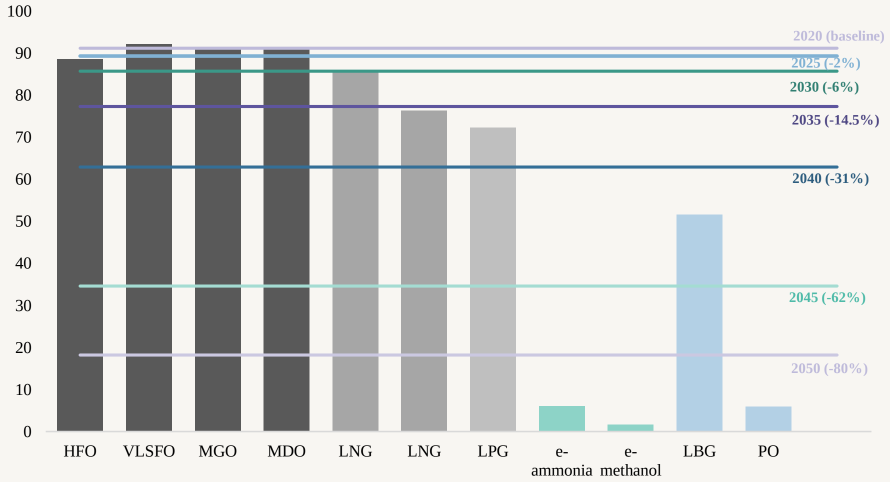


Figure 6: Eligibility timeline for marine fuels under the FuelEU Maritime Regulation. Here dark grey represents oil-based fossil fuels, light grey represents gas-based fossil fuels, green represents e-fuels and blue represents biofuels. [32].

2.1.3.2 *Promoting RFNBOs*

FEUM legislation sets a sub target of 2% RFNBO use by energy content by 2034, contingent upon the industry's failure to achieve 1% RFNBO uptake in 2031. Shipping companies have the option to forgo RFNBOs, provided they use advanced biofuels, or low-carbon hydrogen(-based) fuels (e.g., derived from nuclear power) delivering equivalent emissions reductions compared to RFNBOs. Problematic feedstocks, otherwise referred to as feed-food biofuels, are explicitly excluded as substitutes for RFNBOs due to concerns for competing demand and possible food shortages as a result.

In addition to the sub target, a multiplier of 2 is applied to any ship that makes use of RFNBO up until the year 2034. This effectively halves the cost for compliance as the volume of RFNBOs required to meet GHG reduction targets is halved compared to a scenario without multiplier. Biofuels and low-carbon hydrogen(-based) fuels do not enjoy the same multiplier.

2.1.3.3 *Pooling Mechanism*

While the FEUM requires individual vessels to comply with the GHG reduction targets, companies can demonstrate their compliance at fleet level and trade compliance credits with other shipping companies. This is known as the pooling mechanism. Its main objective is to provide shipping companies with an incentive to deploy new vessels running on (near) zero emission fuels, instead of improving the performance of existing old vessels by blending drop-in biofuels with fossil fuels This is a lesson learned from the road transport sector in the EU under RED I, which left the industry at the mercy of unscalable biofuels and causing significant sustainability issues as a result.

To illustrate how the pooling mechanism works, **Figure 7** considers a shipping company with five vessels. It can decide to replace one of its Very Low Sulfur Fuel Oil (**VLSFO**) vessels with a new dual-fuel ammonia-VLSFO-powered vessel and run it at a mix of 40%-60% respectively while maintaining the operational profile of the remaining four ships. The single partially ammonia-powered vessel would reduce the average GHG intensity of the fleet enough to meet the required reductions until 2034. When it needs to pass the next threshold in 2035, the company can choose to increase the share of ammonia in the new vessel or replace another vessel with a dual fuel engine. This way renewal of assets is stimulated.

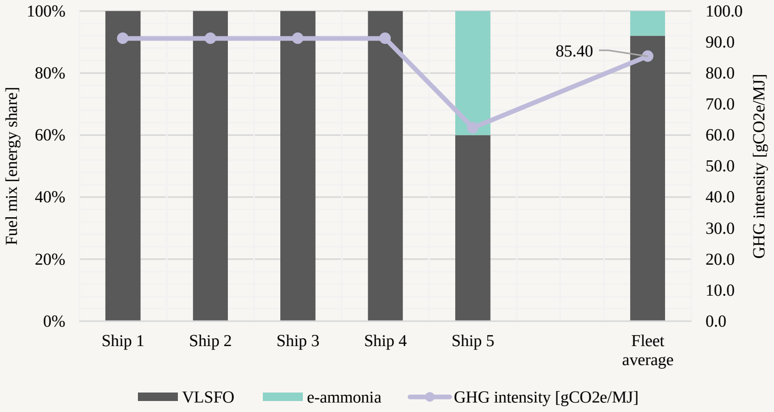


Figure 7: A possible compliance strategy under FEUM. [32]

Pooling can also be used across different shipping companies. For example, if a company chooses to invest in an ammonia-capable ship and fully power it with e-ammonia in 2030, it will likely overshoot its compliance requirements. The surplus may be sold to other companies via the pooling system. FEUM also provides a ‘Banking and Borrowing’ system, which allows companies to store over-compliance for future use or borrow compliance units (at a 10% penalty) from future years to be used in this one. The impact on total emissions will remain identical with or without Banking and Borrowing.

2.1.3.4 Shoreside Electricity

FEUM requires passenger ships and containerships exceeding 5,000 GT to use shore side electricity (**SSE**) or alternative equivalent zero-emission energy sources at berth in EEA ports from 2030 onwards. The mandate is limited to electrical power demand (i.e., excluding heat or steam energy needs) and applies only to ships at berth and not to ships at anchorage. Additionally, the mandate applies only to berths in main logistical ports.

AFIR mandates main logistical ports to install enough SSE stations to meet the relevant electricity needs of container and passenger ships calling at those ports. From 2035, if SSE is available in ports not covered by AFIR, ships are required to use it.

Unlike the overall GHG intensity targets of the FEUM, alternative compliance mechanisms for berth will be accounted for only on a TtW basis. This means that if ships choose not to connect to SSE, the alternative technologies they use may not emit any GHG or air pollutants (i.e., SO_X, NO_X, Particulate Matter) into the atmosphere. As a result, sustainable fuels containing C-atoms (e.g., e-methanol or biofuels) will not be compliant even if they could theoretically deliver zero-emission on a well-to-wake basis, providing an advantage to ammonia.

2.1.4 Compliance

2.1.4.1 Monitoring, Reporting Verification

By 31 August 2024, shipping companies will have to submit a monitoring plan for each of their ships to certified verifiers. Then, from 1 January 2025, shipping companies will be required to monitor and record information on their ships’ voyages. By 31 January 2026, and every year thereafter, companies will need to submit an annual FuelEU report, including Bunker Delivery Notes (**BDN**) to provide the GHG intensity and sustainability characteristics of the fuels used. The certified verifiers are then responsible for calculating the GHG intensity of the energy used on-board by ships, and to verify the measure of compliance. The EU Commission will develop an electronic FuelEU database, where compliance information for each ship will be recorded. There is no legal guarantee that the FuelEU database will be merged with the existing monitoring system used for ETS purposes, named EU MRV. However, this is expected to be the case. More on the MRV database in the following section.

2.1.4.2 MRV Database

The Monitoring, Reporting and Verification (**MRV**) is a requirement to provide and verify shipping emissions data applicable to all ships that exceed 5,000 GT and moored at least once in an EEA port. The legislation was introduced in 2017. Since its introduction, shipping companies are required to submit a monitoring plan within two months after the respective vessel called at an EU port. The content of this plan is predefined by the EU MRV regulation. The monitoring plan needs to be verified by an accredited and independent verifier [35]. Once approved, the shipping company is required to keep and share logs on bunkering, voyage and external data which are then verified and added to the publicly available database [36].

2.1.4.3 *'Pay to Comply'*

Shipping companies that fail to meet the GHG reduction targets will be subject to a penalty but will not have to comply after paying. In essence, FEUM serves as a pay-to-comply mechanism. However, the penalty is increased incrementally by 10% for each year of repeated non-compliance. Member states have the authority to ban ships that fail to pay their dues for two consecutive years but are in no way obligated to do so. Annex V of the FEUM legislation contains the following two equations used to first calculate the level of compliance [3] and subsequently the size of the penalty given [4].

$$CB\left[gCO_{2eq}/MJ\right] = \left(GHGIE_{target} - GHGIE_{actual}\right) \times \left[\sum_{i}^{n,fuel} M_i \times LCV_i + \sum_{i}^{l} E_i\right] \qquad [3]$$

The compliance balance equation uses the target-shortcoming of a ship i.e., $\boldsymbol{\Delta GHGIE}$, and multiplies is by the total mass of each type of fuel used $\sum_{i}^{n,fuel} \boldsymbol{M_i}$, the lower calorific value of each fuel $\boldsymbol{LCV_i}$, and their respective emission factor for each fuel $\sum_{i}^{l} \boldsymbol{E_i}$.

$$Penalty[€] = \left(CB/GHGIE_{actual}\right) \times 41.0 \times €2400 \qquad [4]$$

Equation [4] calculates the penalty based on the compliance balance. The compliance balance is divided by the actual GHG Intensity $\boldsymbol{GHGIE_{actual}}$, which is converted to tonnes of VLSFO using the conversion factor of **41GJ/t** and multiplied by a penalty rate of **€2400**. This means that for every tonne of VLSFO equivalent of excess GHG emissions, shipping companies are penalized €2400 in their first year of non-compliance. The penalty rate increases by 10% annually for continued violation.

Penalty revenues are added to member states' budgets and are earmarked for initiatives that accelerate the use of renewable and low-carbon fuels in the maritime industry. Such initiatives can include promotion of local RFNBO production, realizing bunkering facilities and establishing SSE facilities. From 2030 onwards, member states will have to produce reports detailing how these budgets have been utilized.

2.2 RENEWABLE FUELS OF NON-BIOLOGICAL ORIGIN

RFNBOs can be produced in various ways and are as clean as the electricity used in their production processes. To ensure the sustainability of RFNBOs, clear agreements have been reached on the definition and production criteria. This chapter explains more on both. Due to the maritime scope of this research only e-ammonia and e-methanol are considered, while in reality more RFNBOs exist. However, these were not mentioned as promising alternative fuels in the shipping experts' outlook [28]**.**

2.2.1 Definition

With regards to electrofuels, the Renewable Energy Directive (**RED**) provides us with an industry definition and a set of production standards for future e-fuels producers. One category of e-fuels was named Renewable Fuels of Non-Biological Origin, which is commonly abbreviated as RFNBOs. RFNBOs are fuels of which "the energy content is derived from renewable sources other than biomass" [37]. In essence, RFNBOs are required to be synthesized using renewable hydrogen (excl. biomass) and CO_2 from fossil sources like flue gases, Direct Air Capture (**DAC**), and other non-renewable natural carbon sources, or nitrogen (**N_2**) captured from the air. The most discussed RFNBOs for the maritime industry are e-ammonia and e-methanol. Here, the prefix 'e' stands for the (renewable) electricity used in its synthesis.

2.2.2 Criteria

RED dictates that greenhouse gas emissions savings from the use of RFNBOs must be at least 70% when compared to fossil fuels in order to be classified as a RFNBO [37]. The RFNBO classification comes with advantages like the 2x multiplier mentioned in section 2.1.3.2. In order to classify, RFNBO producers have to report on the electricity source used in the production process. Various configurations are possible [37]:

- **Behind the Meter (BHM) strategy**: Here, the production plant of RFNBO is considered to run on 100% renewable electricity and demands no electricity from the grid. It is therefore considered emission-free.

- **Grid strategy**: If the production process relies on grid electricity, the average share of electricity from renewable sources in the country of production is used. This average share of renewable electricity can only count non-biomass renewable energy.

- **Hybrid**: Producers have their own renewable energy plant but substitute with grid electricity. The shares are determined based on kWh per annum. The same rules apply to the share of electricity drawn from the grid.

In order to meet the requirement of 70% GHG reduction to qualify for RFNBO status, a very high share of renewable electricity is needed: at least ~80% is necessary as can be seen in Figure 8 [a].

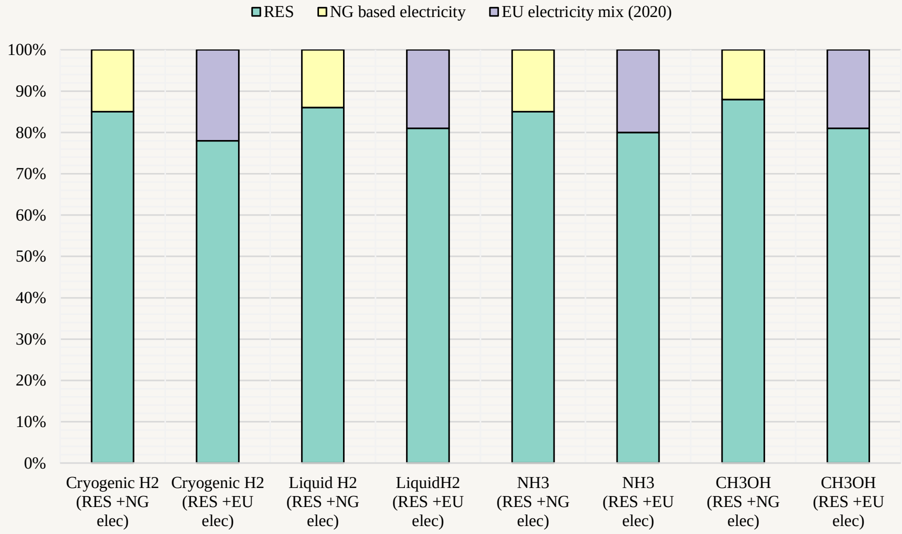


Figure 8: RFNBOs: Share of renewable electricity required to meet 70% carbon savings under RED criteria. [38]

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[a] In this figure a division is made on whether renewables are complemented by a standalone gas turbine or by the grid with average carbon intensity of the EU28 electricity mix. This figure shows the approximate shares of RES required to meet. The analysis conducted to make this figure is based on an electrolysis efficiency of 76% and a carbon intensity of EU electricity mix = 86 g CO2e/MJ [32].

2.3 MARE-FUEL

This section delves into the MarE-Fuel project, which has served as a foundation for this thesis [39]. First the rationale behind the collaboration with the research group is argued. Then, the objective function of a minimization model, featured in one of the project's publications is examined [40]. Finally, a brief contextual background is presented on the modelling approach employed to solve the objective function.

2.3.1 Collaboration

In order to understand how FEUM might impact the fuel demand of the EEA-operating fleet, it is crucial to view the situation from the perspective of shipping companies. These companies shoulder the costs for fuel and equipment and base their investment strategies on profit optimization and regulatory compliance. The decisions made on fuel usage, carry considerable weight in this sector as ships have long average lifetimes and engines and fueling systems cost millions [41]. Consequently, shipping companies use cost minimization models to maximize profitability and hedge risks [42].

Researchers from the Technical University of Denmark (**DTU**) working on a project called MarE-Fuel, built a model to estimate the Total Cost of Ownership (**TCO**) for a fleet operator using various sustainable maritime fuels [43] [44] [45]. Then the research group published a roadmap illustrating various decarbonization pathways [40]. The scope of these publications pertained to the global merchant fleet and the group modelled various theoretical decarbonization pathways (e.g., linear 70% WtW reduction in 2050). A collaboration was established between the author of this thesis and members of the research group. With their help, the author gained knowledge and experience on the SEAMAPS model. With regards to MarE-Fuel project, this thesis varies in both in scope and constraints, which were adjusted to suit the EEA-operating fleet and FEUM legislation. **Chapter 3** delves into model adaptation, constraint building and data sourcing.

2.3.2 SEAMAPS model

2.3.2.1 Objective function

The SEAMAPS model is designed to calculate an optimized future fuel mix through the lens of shipping companies by minimizing for fuel and vessel cost [40]. The model integrates a wide variety of different inputs, variables, and constraints, and minimizes for an objective function (**OF**), which in this case is costs of fuel related costs to shipping companies expressed in millions of euros [€M]. Other outputs include the optimal fuel mix per annum, sector emissions, status of the ship stock and the number of Internal Combustion Engines (**ICE**s) at sea categorized by type. Figure 9 shows an overview of the model methodology.

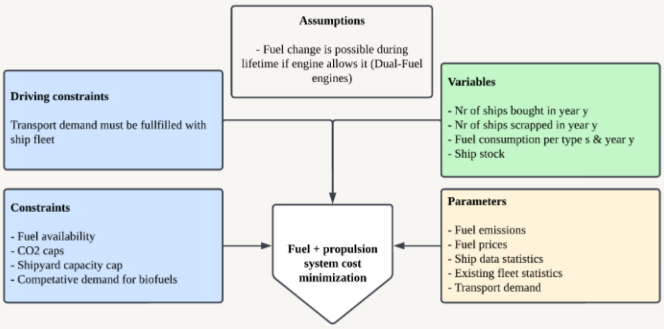

Figure 9: Overview of the ROADMAP model methodology. [40]

The model's minimization process commences when all necessary input data is appropriately prepared. The software uses a cost minimization function as its objective, aiming to find the most economic fuel mix options for the maritime industry at any given scenario. The objective function is minimized to achieve this goal. The formula for the objective function is shown below:

A $$min_{x,q,z,d}{}^{EF} \sum_{s,y} SI_s \cdot NewBuildShips_{s,y} + SOM_s \cdot ShipStocks_{s,y} + SI_s \cdot Decom_{val} \cdot Decommissions^{EF}_{s,y}$$

B $$+ \sum_{s,f,y} FuelUsed_{f,s,y} \cdot FC_{f,y}$$ [b]

The components of this equation can be broadly categorized into two main sections:

A **Fleet-Related Costs**: This category encompasses all expenses associated with the fleet. It is subdivided into three parts that include the investment costs (**CAPEX**) for acquiring additional vessels, the operational and maintenance costs (**O&M**), and decommissioning costs. The model assumes a penalty for discarding an existing ship before its expected lifespan ends, costing half of the ship's original investment value.

B **Fuel Costs** This part is solely focused on the expenses related to fuel. It calculates the total fuel cost by multiplying the fuel consumption of each ship in the fleet by the cost of the fuel, which may also include fuel taxes.

2.3.2.2 Non-Convex Mixed Integer Quadratically Constrained Programming

The type of modelling employed is called Non-Convex Mixed-Integer Quadratically Constrained Programming (**MIQCP**), which is a class of optimization problem where a subset of unknown variables are integers, and constraints are quadratic [46].

Burer, et al., have shown that any nonlinear function, e.g., sine functions, can be exactly or approximately converted into quadratic functions. [47], This implies that an extremely broad range of optimization problems can be represented by MIQCPs. For this reason, MIQCPs have now been employed by researchers for many practical applications including power grid optimization [48] and network design [49].

The commercial solver software used in this model is GUROBI, which employs an algorithmic technique which is particularly effective for solving MIQCP, called the ‘branch-and-cut’ technique [50]. In branching, the algorithm divides the problem into smaller subsets by making decisions on integers. This way, different solutions are systematically explored by carving off parts of the solution space until a solution is found or a termination condition is met.

In cutting, extra constraints are added called cutting planes. These tighten problem relaxation and help eliminate parts of the solution space which do not contain optimal solutions. This helps to approximate the integer programming problem more closely.

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[b] The explanation of the arguments found in this equation is presented in **Annex A**

2.3.3 Fuel supply

Due to the high energy requirement for production, the availability and price of RFNBOs is for a large share dependent on the availability and price of electricity. These potentials differ across spatial planes, as some regions of the earth have higher and more consistent renewable potential than other places. The MarE-fuel project conducted a series of techno-economic analyses to reveal the projected costs of fossil fuels, biofuels, and synthetic fuels. This section discusses the methodology employed by the research group. **Section 3.3** reveals which data from these analyses were used as input for the model adapted for this research and why.

2.3.3.1 Production Locations studied by MarE-Fuel

The MarE-fuel project calculates the Levelized Cost of Electricity (**LCOE**) for offshore/onshore wind, PV, and grid for port locations in Australia (Ceduna), Chile (Arica), Denmark (Esbjerg) and Western Sahara (Dakhla). As shown in Figure 10, locations vary significantly in renewable potential. The analysis reveals that the electricity mix and LCOE vary strongly per location as well.

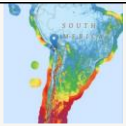
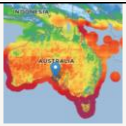
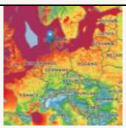
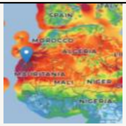
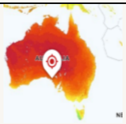
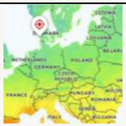
	Arica (Chile) Low wind Very high sun	Ceduna (Australia) High wind High sun	Esbjerg (Denmark) Very high wind Low sun	Dakhla (Western Sahara) Very high wind Very high sun
Wind Resource				
Solar Resource				

Figure 10: Solar and wind potential in different sites considered in the MarE-fuel Project. [43]

2.3.3.2 Electricity supply strategy impacts modelled by MarE-Fuel

The LCOE per location was used as input for an optimization model that finds the ideal plant configuration per location based on the three strategies for satisfying electrical supply outlined in **section 2.2.2**. **Figure 11** and **Figure 12** show the outcome of an emissions analysis which considers infrastructure emissions and energy storage losses. The figures show the differences in WtT emissions for a BHM and a Hybrid strategy. The production of ammonia using BHM emits 8 gCO_{2eq}/MJ_{NH3} whereas the hybrid strategy emits more than six times that amount. The grid connected strategy is least favorable in terms of emissions and is not depicted as a result.

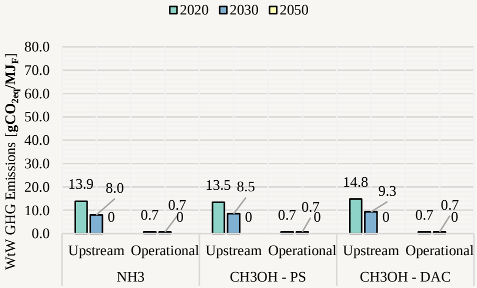


Figure 11: WtT fuel emissions at Dakhla using an off-grid strategy. [40]

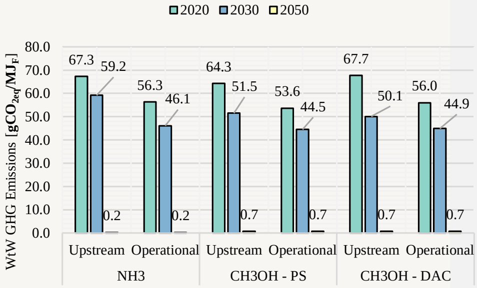


Figure 12: WtT fuel emissions at Dakhla using hybrid strategy. [40]

2.4 POWER-TO-FUEL

A brief description of Power to Fuel (**P2F**) production pathways is provided in this section, with the goal of investigating the precursors that go into E-ammonia and E-methanol production. For a specific overview of other RFNBO production methods, please consult the 2022 EU status report on technology development [51].

The supply chain of RFNBOs is made up out of several conversion steps, starting with renewable electricity and non-biological carbon or nitrogen. In the production of E-methanol, CO_2 and H_2 are reacted directly through the methanol synthesis. In case of E-ammonia, N_2 and H_2 are bound directly through an electric Haber-Bosch reaction. For other e-fuels such as methane and Fischer-Tropsch hydrocarbons, a reverse water gas shift reaction is needed to convert CO_2 to CO, prior to the catalytic synthesis process where the products are formed [51]. **Figure 13** shows a schematic overview of all conversion steps involved in making RFNBO e-fuels.

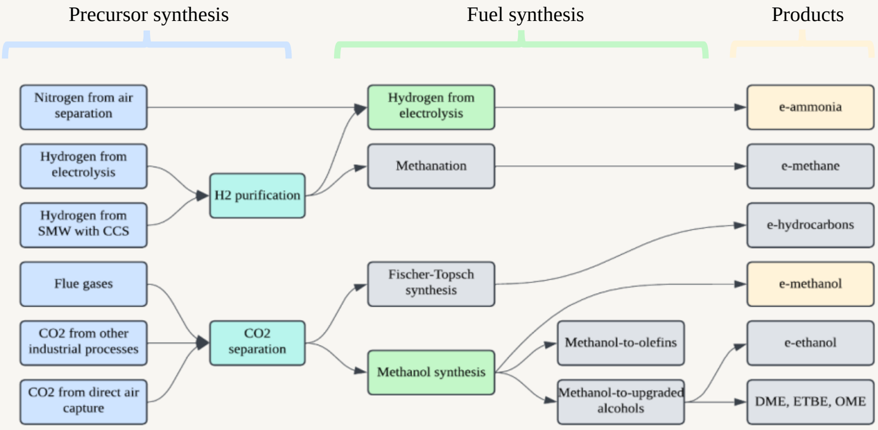


Figure 13: Production pathways of various synthetic fuels. Grey indicates steps which are excluded from this research study. [51]

2.4.1 Precursor synthesis

This section examines the theoretical foundations of precursors necessary for RFNBO production. Various synthesis methods are discussed as well as insights into existing market dynamics surrounding these compounds.

2.4.1.1 Hydrogen Production

In 2022, the production capacity for hydrogen in the EEA is estimated at 11.5 Mt/y as part of a global production capacity of 124 Mt/y [52]. The EEA's production capacity can be divided into unabated thermal production methods such as Steam Methane Reforming (**SMR**) and partial oxidation which collectively produce 95.8% of annual H_2 output and more sustainable methods such as byproduct electrolysis (3.6% of annual output), SMR + CCS (0.5%) and water electrolysis (0.2%) [53] [54]

The SMR process consists of three steps: reforming, where NG reacts with water vapor at supercritical temperatures of 800 °C, the water-gas shift (**WGS**) reaction which increases the hydrogen content (i.e., H_2/ CO ratio) and gas purification, which separates CO_2 from the syngas [55]. The net reaction is shown in **equation [5]**. The emission intensity of this production route is roughly 8-10kg CO_{2eq}/H_2 [54].

$$CH_4 + 2H_2O \rightleftarrows CO_2 + 4H_2 \qquad \Delta H = 165\ (\tfrac{kJ}{mol}) \qquad [5]$$

Water electrolysis is the process of splitting liquid water (**H_2O**) into H_2 gas and O_2 gas by making use of the electrical potential difference between an anode (+) and cathode (-). If renewable electricity is used to power the reaction, then the hydrogen output is labeled as green hydrogen, which is the preferred type used in RFNBO production. The carbon intensity of green hydrogen lies between 0.5 – 0.8 kg CO_{2eq}/H_2 depending on the renewable energy source used [54]. The reactions for water electrolysis are provided below:

Net $$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g) \qquad \Delta H = 285.8\ (\tfrac{kJ}{mol}) \qquad [6]$$

Anode $$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \qquad [7]$$

Cathode $$2\,H_2O + 2e^- \rightarrow 2OH^- + H_2 \qquad [8]$$

There are three routes for water electrolysis: alkaline electrolysis (**AE**), proton exchange membrane electrolysis (**PEME**), and solid oxide electrolysis cell (**SOEC**). **Table 1** presents an overview of the main characteristics of these production methods. By the end of 2022, AE accounted for 60% of installed capacity followed by PEME with 30%. SOEC represents < 1% of installed capacity today [56].

Table 1: Characteristics of various electrolyser technologies.[57]

Character	AE	PEME	SOEC	Unit
Operating temperature	20-80	20-80	600-1200	°C
Operating Pressure	3	7	0.1	MPa
H2 purity	99.5	99.9-99.99999	99.9	%
Efficiency	50-78	50-80	>80	%
TRL	Mature	Mature	6-7	-

Of these three types, AE is the most well-established technology. It is used for production on a large scale and has been commercially available for decades [58]. The cells usually operate between 60 and 80 °C and can run at atmospheric or higher pressures [59]. The key advantages are that it is relatively cost-effective, it uses no noble metal catalysts, and components have a long lifetime. Main drawbacks include medium efficiency (50–78%), high O&M costs due to corrosiveness, and poor dynamic behavior which is unfavorable for effective coupling with renewable energy sources [57] [52].

PEME is gaining significant traction due to its higher flexibility and larger operating range compared to AE. This makes it more suitable for renewable electricity integration. In addition, the purity level of produced hydrogen is higher, and the footprint is lower. However, a major drawback of PEME is the high Capital Expenditure (**CAPEX**), otherwise known as investment costs, associated with the noble metal catalysts required [60].

SOEC is still in the laboratory phase with a reported Technological Readiness Level (**TRL**) of 6 out of 9 [61]. SOEC offers impressively higher efficiency of 93% Higher Heating Value (**HHV**). The operating temperature lies between 650 – 1000 °C [62]. Due to the thermodynamically more favorable conditions compared to the other two production methods, less electrical input is required. The high operating temperatures do imply slow ramp rates and therefore limited operational flexibility. Despite having reached a TLR to be able to support large demonstration units, R&D is still required for material related challenges which have to be tackled in order to guarantee large scale deployment. Finally, SOEC could prove to be very efficient and low impact, but only if coupled with an emission-free heat source [63].

The EU has set a target for local production of 10 Mt of H_2 per year, which requires a staggering 120GW of electrolyser capacity [64]. As previously stated, water electrolysis still accounts for a very limited share of current generation capacity. Therefore, aggressive growth is needed to meet these targets. Current estimates are that the total installed capacity in the EEA (incl. UK) increased from 85 MW in 2019 to 162 MW in 2022 [54]. By the end of 2023, short-term estimates vary between at least 191 MW and an optimistic 500 MW installed capacity [52]. Roughly 1.4 GW of capacity is planned to enter operation in Europe by the end of 2025 [65]. Germany has the largest installed capacity [66]. PEME seems to be the technology of choice for almost 60% of European capacity (84 MW) and alkaline 40% (57 MW) [54]. ~60% of the installed electrolysis capacity is connected to the electrical grid, 23% to dedicated renewable sources and 17% is both connected to a dedicated source and the grid. The latest available data indicates that global capacity will reach the 2 GW mark by the end of 2023 [67].

2.4.1.2 Point Source Filtration

Carbon Capture and Utilization (CCU) is the process of capturing CO_2 and transporting it via pipelines to where it can be used in industrial processes. CO_2 is most effectively captured at point sources like fossil fueled energy transformation plants, and heavy industry like cement and steel production. The filtration happens via adsorption and absorption at the very end of the smokestack where flue gasses would normally be emitted as a result of fossil fuel combustion [68]. These CCU technologies can reduce point source emissions by 80–90% [69]. However, running such processes is energy-intensive and increases Final Total Consumption (**FTC**) of the plant by 10–40% [70].

2.4.1.3 Direct Air Capture

Direct Air Capture (DAC) installations are engineered to filter CO_2 directly from the atmosphere, thus undoing preciously emitted carbon [71]. A key challenge for DAC is the low concentration of CO_2 in the atmosphere compared to point sources. Therefore, DAC systems need to process large volumes of atmospheric air to obtain a limited amount of CO_2 while energy requirements are significant. Although the technology is still quite novel and the business case very dependent on carbon pricing, DAC stands out in that it is truly net negative in contrast to point source filtration [72]. The energy requirements for DAC are typically 98.1 kJ/mol CO_2.

2.4.1.4 Nitrogen Air Separation

Nitrogen (N_2) is filtered out of the atmosphere in a similar fashion to CO_2 using DAC technology. The main difference is that N_2 is far more abundant in the earth's atmosphere. The process is therefore much less energy intensive at 29.23 kJ/mol N_2. The process can be fully carbon neutral and purity levels of 99.9995% can be achieved [73].

2.4.2 Fuel Synthesis

This section covers fuel synthesis and delves deeper into the Haber-Bosch and CO_2 hydrogenation processes that produce the RFNBOs relevant to this research.

2.4.2.1 Haber Bosch Process

Ammonia (**NH_3)** is a crucial chemical building block for many commercial and household applications such as refrigerant and cleaning agents. However, the element is most widely used for fertilizer production [74]. The global production volume of NH_3 exceeds 170 million metric tons per annum [75]. It is supported by well-established infrastructure and a century of scientific research, meaning there is extensive knowledge on storage and transport.

Ammonia is synthesized via the Haber-Bosch (**HB**) process, which bonds the precursors H_2 and N_2 at high pressures (100 – 450 bar) and temperatures (~500 °C) [76]. The exothermic reaction takes place in presence of several catalysts. Although the reaction itself is exothermic, driving it forward requires significant initial energy input. The net reaction formula is:

$$\frac{1}{2}N_2 + \frac{3}{2}H_2 \leftrightarrow NH_3 \qquad \Delta H = -91.8\ \left(\frac{kJ}{mol}\right) \qquad [9]$$

The NH_3 produced is color coded based on the energy source and H_2 production method used. 'Grey' NH_3 (using natural gas for HB units and SMR derived H_2), emits 2.6 kg CO_{2eq}/NH_3 in its lifecycle [77]. The vast demand for grey NH_3 makes it the most energy intensive and GHG emitting chemical, demanding 2% of global Total Final energy Consumption (**TFC**) and emitting 1-2% of annual CO_{2eq} emissions in the process [33]. It is possible to capture substantial volumes of the CO_2 post-combustion at a cost and energy premium as will be explained in **section 2.4.1.2.** This produces 'blue' NH_3, which is low GHG intensive. The production process for grey/blue ammonia is depicted in **Figure 14**.

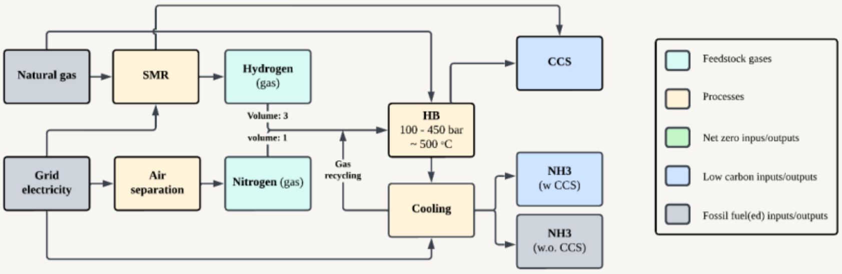


Figure 14: Simplified flow scheme grey/blue ammonia production. [78]

Using electrolysis-derived hydrogen and electrically powered air separation and HB units results in 'green' NH_3 provided that renewable electricity is used. This environmentally friendly production method emits virtually no GHG emissions and is depicted in **Figure 15**.

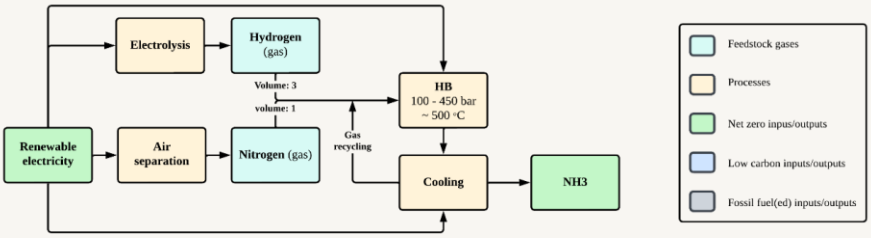


Figure 15: Simplified flow scheme of e-ammonia production. [78]

2.4.2.2 CO_2 Hydrogenation

Methanol (**CH_3OH**) is the simplest alcohol and an important feedstock that is used in the synthesis of various chemical commodities [79]. These chemicals include methyl tertbutyl ether (**MTBE**), dimethyl ether (**DME**), formaldehyde, and acetic acid. Derivatives of this feedstock can be found in numerous products like plastics and paints [57]. In 2022, the global methanol production volume exceeded 110 million metric ton per year [80]. A quarter of this was used for fuel applications [81]. The life-cycle emissions from conventional methanol production and use are around 0.3 gigatons (**Gt**) of CO_2 per year, constituting ~10% of total chemical sector emissions [82]. The production of methanol has nearly doubled in the last decade. Under current trends, production is expected to increase to 500Mt per year in 2050 [83].

Methanol is the product of a process called CO_x hydrogenation, which fuses CO_x and H_2 molecules in a highly exothermic reaction [84]. The two gasses react under relatively 'soft' conditions (210-270 °C and 50 – 100 bar) due to a catalyst [85]. The net reaction equations for both CO_2 and CO hydrogenation are:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH \ + \ H_2O \qquad \Delta H = -49.5 \ (\frac{kJ}{mol}) \qquad [10]$$

$$CO + H_2O \leftrightarrow CO_2 \ + \ H_2 \qquad \Delta H = -41.0 \ (\frac{kJ}{mol}) \qquad [11]$$

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \Delta H = -90.5 \ (\frac{kJ}{mol}) \qquad [12]$$

Again, the color code of the commodity is determined by the energy used in its production processes. The majority of CH_3OH produced is 'grey' CH_3OH, which utilizes both the heat and chemical outputs from the SMR process (CO_x and H_2). The lifecycle GHG emissions associated with production method are 2.2 kg CO_{2eq}/CH_3OH [86].

Blue hydrogen CH_3OH uses green or blue hydrogen and CO_2 captured via PS filtration. Green CH_3OH, also known as E-methanol, is produced using green hydrogen (i.e., produced with renewable electricity) and CO_2 captured from renewable sources such as DAC or bioenergy with CCS. However, when using CO_2 from bioenergy sources, E-methanol cannot be certified as an RFNBO.

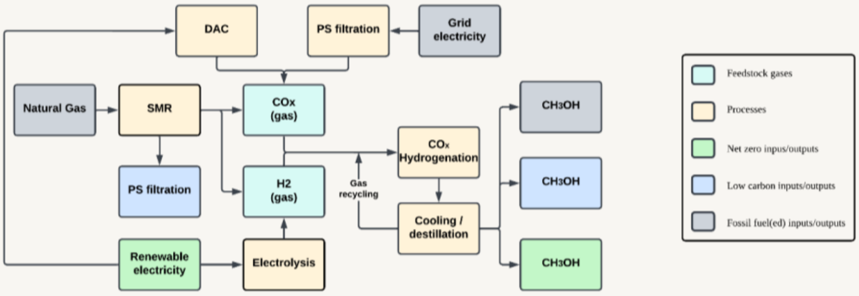


Figure 16: Simplified flow scheme of COx hydrogenation foe producing grey, blue and green CH3OH

2.5 MARINE FUEL CHARACTARISTICS

When considering alternative fuels, it is important to consider their chemical properties. A mix of fuel performance, energy content, handleability and emission profiles need be a net improvement over current fuels in order to be considered as a viable candidate. Additionally, hazards to humans and wildlife need to be within acceptable ranges. This section describes the characteristics marine fuels currently in use or under review. These include the RFNBOs in scope as well as some biofuel alternatives. **Table 2** shows the fuel state, Lower Calorific Value (**LCV**), better known as the energy content and the GHG profiles per GHG. **Annex C** contains a comparable table using different units used by independent verifiers. [34]

Table 2: Energy content and GHG intensity of various marine fuels

				gCO$_{2e}$q/MJ - 100 yrs.				
	Fuel type	State	LCV	WtT	TtW CO$_2$	TtW CH$_4$	TtW N$_2$O	WtW
Fossil fuels	VLSFO	Liquid	41.0	13.2	77.6	0.2	1.1	92.1
	MGO	Liquid	42.7	14.4	75.1	0.2	1.1	90.8
	LNG	Gas	49.2	18.5	56.1	1	0.7	76.3
	LNG_Cslip	Gas	49.2	18.5	56.1	10.4	0.7	85.7
	LPG	Gas	46.0	8.3	66.0	0.2	0.7	75.2
RFNBO	E-Ammonia	Liquid	18.6	0	0	0	5.3	5.3
	E-Methanol	Liquid	19.9	0	0	0.2	0.7	0.9
Biofuels	PO	Liquid	16.3	5.9	34	0.2	1.1	41.2
	LBG	Gas	50	27.8	16.7	10.4	0.7	55.6

2.5.1 Fossil Fuels

2.5.1.1 HFO/VLSFO

Heavy Fuel Oil (**HFO**) is an umbrella term that aggregates a variety of marine fuels [87]. Most residual fuels fall into this category. These are one of the lowest-value petroleum products from a refinery and are in essence a byproduct of producing the light products, which are the primary focus of the distillation process [16]. Due to the negative externalities to human health and environment caused by the sulfur oxides (**SO$_x$**) and NO$_x$ in HFO emission gas, regulations, otherwise known as emission control areas (**ECAs**) have been put in place to limit for instance, the sulfur content of HFO's to 0.5%. The result is very low sulfur fuel oil (**VLSFO**), which is plain HFO treated for sulfur. In 2021, 74% of all EU related voyages were propelled by these two fuels [88].

2.5.1.2 MGO/MDO

Marine gas oil (**MGO**) is a light distillate fuel and therefore by definition, more expensive than refinery byproducts such as HFO. Marine diesel oil (**MDO**) is a blend of HFO and MGO making it heavier but more cost-effective than MGO. Both fuels are cleaner alternatives to HFO/VLSFO and are compliant with the strictest ECA regulations [89].

2.5.1.3 LNG/LPG

Liquefied Natural Gas (**LNG**) and Liquefied Petroleum Gas (**LPG**) are gaseous fossil fuels that have relatively low TtW GHG emission profiles as well as relatively good SO$_x$, NO$_x$, and particulate Matter (**PM**) emissions. LNG, which is primarily methane (**CH$_4$**), has gained a lot of interest as an alternative to HFO/VLSFO. Currently 47% of marine vessels on order will be propelled by LNG [90]. However, WtW emissions of LNG can be similar to HFO/VLSFO, if used in certain engines. These engines slip CH$_4$, which itself is a very potent GHG [91].

LPG is a mixture of propane (**C$_3$H$_8$**) and butane (**C$_4$H$_{10}$**) and is used in applications such as heating and cooking. It is not a GHG and therefore slipping is not an issue. Both LNG and LPG have to be transported and stored in a liquid state which means storage using low temperatures, high pressures, or a combination thereof [92]. However, the boiling point of LNG is much lower (-162 °C) than LPG (-42 °C) meaning more energy is required for the phase change.

2.5.2 RFNBOs

2.5.2.1 E-Ammonia

NH_3 has an extraordinarily high gravimetric hydrogen density (17.75 wt%), this and the absence of carbon (**C**) in its molecule has given it significant attention as a RFNBO[93]. Compared to hydrogen, it is relatively easy to transport as its boiling point sits a relatively 'high' -33 °C (1 bar) compared to -253 °C [94]. NH_3's low viscosity and relatively high energy density make it a suitable option for long distance shipping [95]. In the liquid state, ammonia has an LCV of 18.7 MJ/kg, which is approximately 2.1 times lower than conventional fuel used; very low sulfur fuel oil (**VLSFO**), resulting in larger tank requirements for ammonia powered vessels. The fuel requires higher ignition energy than fossil fuels due to its low volatility [96]. The eyecatcher that draws attention to NH_3 as a fuel is it contains no C atom, which means no direct CO_2 emissions. If upstream processes are fully decarbonized, one is left with a net zero fuel. However, combusting NH_3 results in nitrous oxides (NO_x) emissions, which play an important role in causing air pollution and acid rain. NO_x emissions are also a common byproduct of fossil fuel combustion and can be reduced using suitable catalysts [97]. The rate of NO_x emissions and NH_3 slippage is to be determined when the first NH_3 powered vessels make waves in 2025 [30].

NH_3 is classified as acutely toxic under category 3 (hazard statement codes: H314, H331, H400) according to EU Regulation 1272/200818 [98]. Ammonia is easily absorbed by inhalation, ingestion, or skin contact. These hazards require strict regulations for specialized equipment and facilities for handling, which are currently limited in the shipping industry.

2.5.2.2 E-Methanol

The gravimetric hydrogen density in methanol is approximately 12.57 wt%; the rest of the molecule is comprised of oxygen (**O**) and C. CH_3OH is liquid at ambient temperature and pressure. This means, that existing gasoline storage and distribution infrastructure would require relatively little modification to operate with CH_3OH [99]. The LCV of CH_3OH is slightly higher than NH_3 at 19.9 MJ/kg while still roughly half that of VLSFO. CH_3OH does emit CO_2. The process could be net neutral, however only if DAC or Bioenergy Carbon Capture Utility (**BECCU**) sourced CO_2 is used. If point source CO_2 emissions are used for the production, carbon is essentially recycled. This means a share of the direct CO_2 emissions needs to be allocated to both the ship and the source of carbon [26]. CH_3OH is classified as acutely toxic under category 3 (hazard statement codes: H301, H311, H331) according to EU Regulation 1272/200818 [98]. Methanol is easily absorbed by inhalation, ingestion, or skin contact. Like with NH_3 these hazards require specialized equipment and handling facilities.

2.5.3 Advanced Biofuels

2.5.3.1 Pyrolysis Oil

Pyrolysis Oil (**PO**) is a liquid fuel which can be produced from a wide variety of biomass feedstocks through the pyrolysis process. In this process, biomass is decomposed due to high temperatures without the presence of oxygen. PO has the lowest calorific value of all the fuels considered in this research at 16.3 MJ/kg [100]. An advantage of PO is that it can be mixed into other liquid fuels or even fully power vessels without the requirement of any modifications to current vessels [101].

2.5.3.2 Liquefied Biomethane Gas

Liquefied Biomethane Gas (**LBG**) is the biofuel equivalent of LNG and is produced via gasification of biomass. Its emissions are highly dependent on the biomass feedstock used. As a fuel it is fully interchangeable with LNG as both consist mainly of CH4 [102]. LBG can therefore be used in any vessel that has LNG carrying capacity and be mixed into a tank with LNG to any rate.

2.6 Marine Engine Technology

Most marine vessels in the >5,000 GT category, rely on diesel engines, which operate on a single fuel (**SF**) two-stroke diesel cycle [103]. The operating speed of these engines is in the low-speed range of 70–120 rounds per minute (**RPM**). The large dimensions and low RPMs of this engine make it well-suited for low-quality fuels like HFO/VLSFO [104]. However, engine technology had and has to evolve to allow for alternative fuels. This section discusses various engine technologies which fall within in scope of this research. The engine types were adopted from literature [40].

2.6.1 Marine Engines

Dual-fuel (**DF**) engines are engines that can operate on two different types of fuel, either simultaneously or interchangeably. Some DF engine combinations are already commercially available, including for methanol. The first ammonia DF engine delivery is expected in 2025. Engines, their fuel handleability and release year are depicted in **Table 3**.

ME-C: Liquid injected **SF** engine using fuel oil. This technology is installed on most of the current fleet.
ME-GI: Gas injected **DF** engine using fuel oil or LNG.
ME-LGIp: Liquid gas injected **DF** engine allowing switching between fuel oil, MGO, & LPG.
ME-LGIm: Liquid gas injected **DF** engine allowing switching between fuel oil, MGO, & methanol.
ME-LGIa: Liquid gas injected **DF** engine, assumed to allow switching between fuel oil, MGO, LPG & ammonia.

Table 3: The various engine types considered, plotted with their fuel handleability. [40]

	First year available	VLSFO / HFO	MDO / MGO	PO	LNG / LBG	LPG	CH_3OH	NH_3
ME-C	2020	✓	✓	✓	✗	✗	✗	✗
ME-GI	2020	✓	✓	✓	✓	✗	✗	✗
ME-LGIp	2020	✓	✓	✓	✗	✓	✗	✗
ME-LGIm	2020	✓	✓	✓	✗	✗	✓	✗
ME-LGIa	2025	✓	✓	✓	✗	✓	✗	✓

2.6.2 Pilot Fuel

If a singular fuel is used, DF engines suffer from higher percentages of unburned fuel and lower thermal efficiency compared to SF engines [105]. To counter this, problem engine producers have figured out that combusting low shares of secondary fuel, also known as pilot fuel, in combination with the main fuel improves the efficiency and excess emissions significantly [106]. Pilot fuels are always liquid and need to be mixed carefully to get the optimum result, which varies per main fuel [107]. The pilot fuel is assumed to be VLSFO until 2039, after which it is substituted by DME (dimethyl ether), which is a synthetic alternative to diesel. The optimal shares of pilot fuel per main fuel are covered in **Table 4**.

Table 4: Type and share of pilot fuel added to main fuels under study. [40]

Main fuel	**2020**	**2030**	**2040**	**2050**	**Share of pilot oil (energy share)**
LNG	VLSFO	VLSFO	DME	DME	**1.50%**
LPG	VLSFO	VLSFO	DME	DME	**3.50%**
Methanol	VLSFO	VLSFO	DME	DME	**5%**
Ammonia	VLSFO	VLSFO	DME	DME	**5%**
LBG	VLSFO	VLSFO	DME	DME	**1.50%**

2.7 SCENARIO THINKING

Scenario thinking is used to cope with and prepare for uncertain future events. It can be used to deal with short term disruptions (such as a financial crisis or a pandemic) or for exploring the effects of long-term developments (e.g., climate change) [108]. Such scenarios provide a structured approach to deal with different factors like future market trends, technological advancements, and policy interventions [109]. In climate research a combined framework of emission concentration and socio-economic scenarios are used. These scenarios are used as input for climate model runs and serve as a basis for the assessment of possible impacts, mitigation options and associated costs [110].

2.7.1 Representative Concentration Pathway

Representative concentration pathways (**RCP**s) are a set of GHG concentration trajectories adopted by and used in modelling of the IPCC [111]. The pathways describe six plausible climate change scenarios, depending on the quantities of GHG emitted in the coming years: RCP1-1.9, RCP2.6, RCP3.4, RCP4.5, RCP6, and RCP8.5. The scenarios are labeled after the predicted radiative forcing values in 2100. Radiative forcing is the net energy balance between incoming and outgoing radiation in the earth's atmosphere. Higher values represent more profound effects of climate change, lower values are more desirable but require more mitigation efforts [112].

2.7.2 Shared Socioeconomic Pathway

Shared Socioeconomic Pathways (**SSP**s) are a set of five scenarios for alternative projected socioeconomic developments up to 2100 [113]. The SSPs are qualitative descriptions of broad development patterns based on quantitative elements such as population, education, urbanization, GDP, and technology. Changes in economic developments and population have strong implications for the anticipated mitigation and adaptation challenges, e.g., large, poor populations will face more difficulties in adapting to climate change effects.

The five SSPs include: a world of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends broadly follow their historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5) [114].

Figure 17 shows the different emission trajectories per SSP while indicating the severity of mitigation challenges and level of adaptation. SSP1 experiences the lowest mitigation and adaptation challenges. This pathway requires the least negative emissions by 2100 to stay within 2 °C. SSP5 experiences low adaptation and high mitigation challenges, meaning the problem is addressed, however not by mitigating fossil fuel consumption. This energy intensive pathway relies heavily on technological innovation.

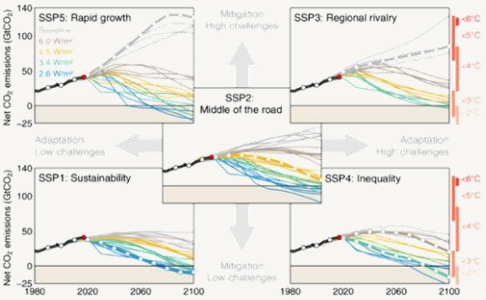


Figure 17: Five Shared Socioeconomic Pathways, developed to explore challenges to adaptation and mitigation.

3. METHODOLOGY

This chapter starts with the creation of four scenarios, which will be used to analyze results. Following this, a section on model constraints is included where retained, added, and omitted constraints are discussed. Subsequently, two sections are dedicated to the model's input variables for the model: Fuel Supply and Future Shipping Demand. These sections individually represent a line in the objective function outlined in **Section 2.3.2.1**.

Once these preparatory stages were completed the model was ready to be executed. This generates many outputs, such as optimal fuel mix, emissions per year and costs per year to shipping companies, which answers sub question two: What is the optimal fuel mix for shipping companies to meet FuelEU Maritime targets per scenario? To answer sub questions three and four on scenario GHG abatement costs and model sensitivity, additional methods were required. This section is called OUTCOME INTERPRETATION. A schematic overview of the employed methodology is illustrated in **Figure 18**.

It is important to note that terminologies in this chapter lack explicit explanations. Instead, cross-referencing is used to direct the reader to the corresponding sections in the theoretical background.

Commented [EK2]: In zijn algemeenheid vind ik de methodologie goed te volgen. Waar mogelijk zou ik naast tabellen nog vaker een figuur zoals op de eerste pagina va de methologie introduceren. Bijv. om onderdelen van de algehele methodologie uit te lichten. Ook zou toch advise om nog meer aan te dikken waarom en welke aanvulling doet op het bestaande onderzoek. Zulke informatie zou ik ook in beknopte vorm naar voren laten komen in de introductie. Dit moet echt blijven hangen voor je professo

In de introductie zou ik meer een samenvatting van de methodologie verwachten. Hier benoem je eigenlijk allee welke vragen worden beantwoord door het verkrijgen van bepaalde variabelen. Maar het gaat mij als lezer meer om aanpak, en in hoeverre deze is gegrond op academische methodologie om dit op deze manier te doen. Om terug te komen op mijn eerste paragraaf in dit punt: in de introdu kan je expliciet zeggen "methodologie bouwt voort op recente wetenschap en maakt gebruik van onderbouwde aanvullingen" blabla. Kijk naar de scoring sheet (rubric) e probeer op strategische wijze dit soort bewoordingen in je tekst op te nemen in samenvattende/introducerende tekst. is een soort signaal naar je professor: "dit valt qua werk in boxje X van de beoordeling"

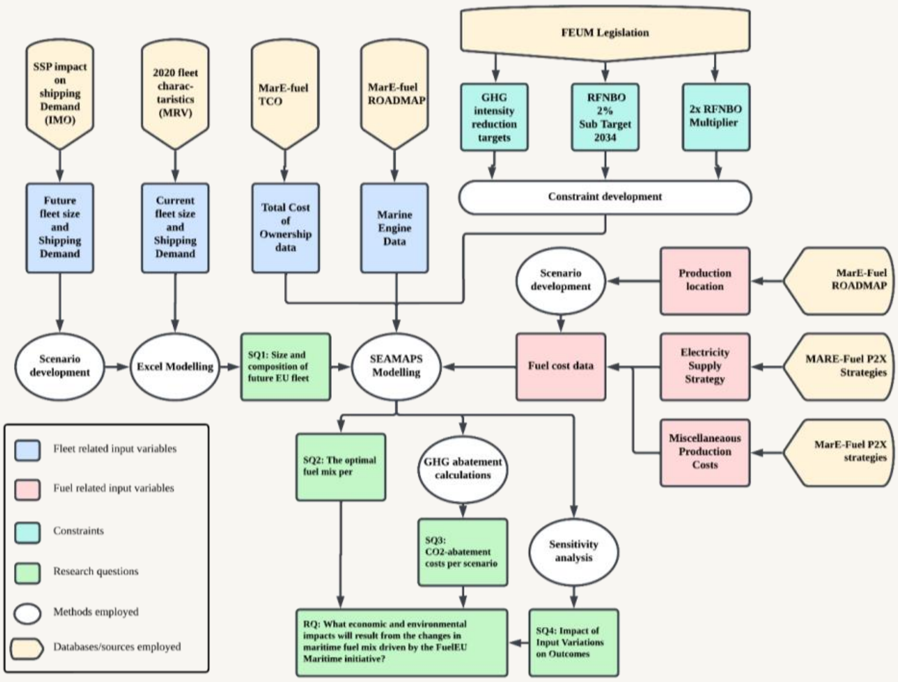


Figure 18: Methodological framework for this research displaying methods employed, techno-economic data gathered, the origin of this data and the outputs obtained.

3.1 SCENARIOS

This study explores four distinct scenarios, each a product of two pivotal variables: The SSPs and the choice of production location. SSP1 and SSP5 share low adaptation challenges but diverge significantly in terms of mitigation challenges. Both pathways can deliver on staying below the 2 °C global mean temperature increase, aligning with the goals set by the EGD. However, instruments employed to stay below 2 °C differ greatly between these two SSPs [115].

SSP3 'regional rivalry' implies a deterioration of the EU and SSP4 'inequality' conflicts with the EGD's objective of fostering a sustainable and inclusive transition to net zero [116]. These SSPs are excluded from consideration due to their high mitigation challenges, making them less likely to meet the 2 °C target and are therefore not aligned with EU targets.

The consideration of two RFNBO production locations as variables to the model adds another layer of intricacy to this analysis with one production location situated in the EEA and one outside of the EEA. Both scenarios are currently being considered by the EU as it has targets of 10Mt hydrogen production, and 10 Mt hydrogen import for 2030 as outlined in **Chapter 0**. The non-EEA location was chosen because of its superior cost-effectiveness to other locations, while the EEA location was picked due its geographical location within the EEA trading alliance [43].

The EEA based RFNBO production facility is located in Esbjerg, Denmark, while the non-EEA facility is located in Dakhla, Morocco. For purpose of this research, it is assumed that all RFNBOs are produced at one location at a time. By extension, Esbjerg is considered representative of all 'local' production and Dakhla is representative of all 'foreign' production. These case factories are a necessary framework for this study.

Figure 19 shows a visualization of the four scenarios explored in this research.

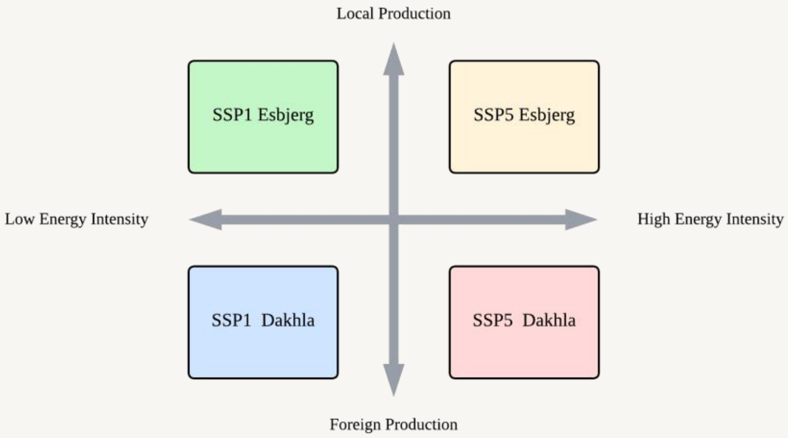


Figure 19: A visualization of the four scenarios under examination in this research

3.2 MODEL CONSTRAINTS

The Objective Function (**OF**) in this research paper was largely adopted from the MarE-Fuel publication, with the exclusion of the fuel tax part. The key differences with this research and the MarE-Fuel publications lie in this research's utilized model constraints and input data so to simulate the effect of FUEM legislation, RFNBO production location and SSPs on the fuel mix of EEA-operating fleet.

The model incorporates constraints to simulate real-world rules and limitations that dictate the allowable values for specific variables. This research builds on five constraints from the MarE-fuel publication, introduces three new ones, and omits one. A detailed overview of these constraints and their descriptions is found in **Table 5**.

Table 5: All model constraints, categorized by whether they are retained, newly added, or omitted for this research.

Status	Name	Description
Constraints retained from original model	Shipping Demand	Aligns shipping supply with the modelled demand projections of the IMO and maintains a balance to prevent discrepancies such as excess shipping supply or demand.
	Ship Stock	Sets an upper boundary to the total number of ships in the EEA-operating fleet per year. It is calculated by taking ship stock one year prior, adding newly purchased ships and subtracting decommissioned ships.
	Ship Capacity Production	Limits the annual purchase of ships of type s and year y by the industry's production capacity in that year. If the engine is not yet available, then production capacity is zero.
	Fuel Consumption	Aligns fuel usage with shipping demand, by multiplying the number of ships of type 's' with their average transport work for each year 'y', using specific fuel consumption rates for each fuel type and ship. The constraint allows for switching between fuel types if the engine is of dual-fuel (DF) type.
	Fuel Availability	Matches the fleets fuel demand in year y to the available fuel supply in that year.
Omitted constraint	Availability & competing demand for biofuels	Limits the amount of biomass available to the shipping industry per scenario.
New constraint added	FEUM targets	Enforces the annual FEUM intensity targets to be met annually. The model can break this constraint by buying 'gap fuel'. A non-existent magic fuel has no emissions and but comes at a cost 10-20 higher than RFNBOs.
	RFNBO 2x Multiplier	Reduces cost of RFNBO by 50% until 2034.
	RFNBO sub target	Verifies if there is 1% RFNBO uptake (by energy content) by 2031; if not met, imposes a minimum 2% uptake requirement by 2034.

The omitted constraint pertains to the availability of biomass for biofuel and the competing demand of various industries to secure these fuels. Given that biofuels are not prioritized the same as RFNBOs in the FEUM legislation, and the complexity of modelling the supply of biomass is enough to warrant a separate thesis, it was decided to leave this constraint out of the paper's focus. Instead, a low biomass availability scenario was adopted.

3.3 FUEL SUPPLY

As mentioned in **Section 2.3.3**, data on fuel production locations originates from two publications of the MarE-fuel publication [43] [44]. This coming section reveals what data was used as modelling input and provides justification.

3.3.1 Production location

As outlined in **Section 2.3.3.1**, MarE-fuel considers four RFNBO production locations. For this research, Esbjerg and Dakhla were selected. Esbjerg since it is the only considered location within EEA borders and Dakhla since it is the most cost-effective location for RFNBO production out of all locations considered. Additionally, the latter is closer to EEA ports than Chile and Australia. This research was required to these locations as the techno-economic data was readily available.

3.3.2 Electricity Supply Strategy

As highlighted in **Section 2.2.2** RFNBOs require a 70% GHG reduction (i.e., max intensity = 28.2 gCO_{2eq}/MJ) compared the fossil fuel baseline of 94 gCO_{2eq}/MJ_F to be certified as such. Examination of **Figure 11** and **Figure 12**, reveals that the minimum threshold is exclusively met in all decades if using the 'Off-Grid' strategy, which eliminates the eligibility of other strategies in 2020s and 2030s. From the figures is can be deduced that all strategies meet the GHG reduction standards in 2050. Sadly, data for 2040 is absent.

This research assumes net-zero emissions from the electricity mix for grids in both selected locations by 2040. As a result, all strategies employed meet the required GHG reduction standard from this year onwards. Therefore, costs from the most cost-effective energy supply strategy were used, which is the 'Hybrid' strategy.

3.3.3 Miscellaneous Production Costs

In addition to production location and electricity supply strategy, the production cost of RFNBOs is influenced by various factors. Key amongst these factors are electrolyser type, RFNBO transportation costs and pilot fuel blending. This section clarifies the electrolyser type selection and delves into the other cost factors, which are derived from the MarE-fuel project.

3.3.3.1 Electrolyser type

As illustrated in **Section 2.4.1.1** PEME is a mature technology and is quickly gaining market share within the EEA due to its many advantages. However, it is excluded from this research due to its reliance on critical materials such as iridium, scandium, and yttrium. The availability of these materials bears risk of hampering the scaling of this technology and could very well slow price reductions [117].

AE currently stands as the most developed technology for producing emission-free hydrogen and substantial cost reductions are anticipated in the coming decades. However, MarE-fuel modelling projects SOEC will likely surpass AE in terms of cost-effectiveness by 2030 [44]. This coincides with the period when RFNBO share in the fuel mix is expected to be modest, aligning with the 2% RFNBO sub target by 2034 as outlined in **Section 2.1.3.2.** Given the expected higher cost competitiveness in comparison to AE and PEME, SOEC technology was selected for hydrogen production in this research.

3.3.3.2 *Transport costs*

For correct comparison it is assumed that all shipping routes have Rotterdam as their destination. The transport costs are calculated using **Equation [13]**.

$$\text{Transport costs}_{s,f}\,[€/GJ] = \frac{\text{cargo costs}_{s,f}}{\text{LCV}_f} \qquad [13]$$

Here, **Transport costs$_{s,f}$** [€/GJ] is defined per production site ***s*** and fuel type ***f***. **Cargo costs$_{s,f}$** [€/t] is the price of transporting a ton of fuel type ***f*** site ***s*** to destination. This data was provided by industry partners of the MarE-fuel project. **LCV$_f$** [GJ/t] is the lower calorific value of fuel ***f***.

The resulting transport costs are shown in **Table 6**.

Table 6: Transport costs from production site to the port of Rotterdam in €/GJ

Transport costs [€/GJ]	Esbjerg	Dakhla
NH_3	0.01	0.31
CH_3OH	0.06	0.29

3.3.3.3 *Profit Margin*

A profit margin for the RFNBO producer is added to the production cost. This margin is assumed to be higher in early years and decline as the supplier's market consolidates. It is 10% in 2020, 7.5% in 2030, 5% in 2040 and 2.5% in 2050. The numbers are based on the average net profit margin of the chemical industry, which currently sits at 5% [118].

3.3.3.4 *Pilot Fuel Blending*

As outlined in **Section 2.6.2**, the price of pilot fuel has to be added to the cost of the main fuel to get the total cost for shipping companies. The pilot fuel is assumed to be VLSFO until 2039, after which it is substituted by DME (dimethyl ether), which is a synthetic alternative to diesel. The price for VLSFO is taken at market value and the price for DME is calculated using production costs and adding profit margin and transport costs to Rotterdam. The resulting fuel costs to shipping companies, which are used as input for the model, are shown in **Table 7**:

Table 7: Final fuel costs per location for shipping companies, by decade and type of RNFBO in €/GJ

Production location	**RFNBO**	**Year** →	**2020**	**2030**	**2040**	**2050**
	↓	**Electricity supply strategy** →	**BHM**	**BHM**	**Hybrid**	**Hybrid**
Esbjerg	MET-PS		61.6	52.1	37.1	29.9
	MET-DAC		73.4	62.5	44.2	35.4
	AMM-green		60.5	46.6	30.2	23.6
Dakhla	MET-PS		48.5	42.3	33.5	27.9
	MET-DAC		57.8	50.7	39.9	33.0
	AMM-green		42.7	33.6	25.0	19.9

It becomes clear from the table that there is a large difference in fuel costs depending on where that fuel was produced. A significant difference exists primarily in the early years of RFNBO production. This difference between Esbjerg and Dakhla reduces over time but never goes away. Dakhla scores better in terms of costs in all decades compared to Esbjerg. Another striking observation is that e-ammonia outperforms both types of e-methanol in terms of fuel costs to shipping companies.

3.3.4 Fuel Input Data

The data from **Table 7**, combined with readily available data on fuel price development were used as input for the SEAMAPS model [40]. **Figure 20** and **Figure 21** show the fuel prices to shipping companies per year, meaning transport, profit margin and fuel blended is added to RFNBO production prices. The difference between these figures is the RFNBO production location. Each datapoint seen in these figures was used as input for the SEAMAPS model.

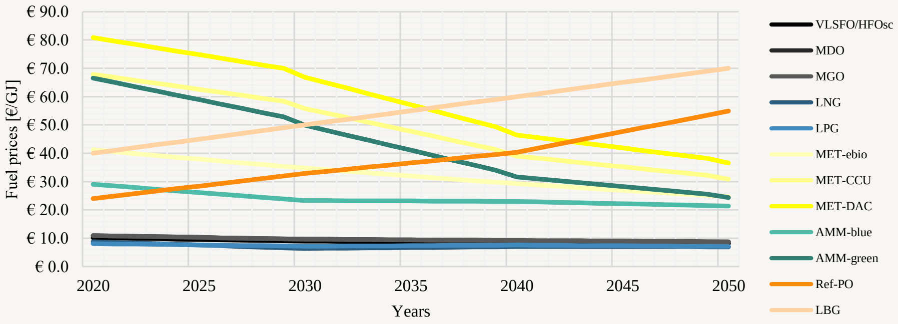


Figure 20: A visualization of marine fuel prices to shipping companies in €/GJ for RFNBO production location Esbjerg

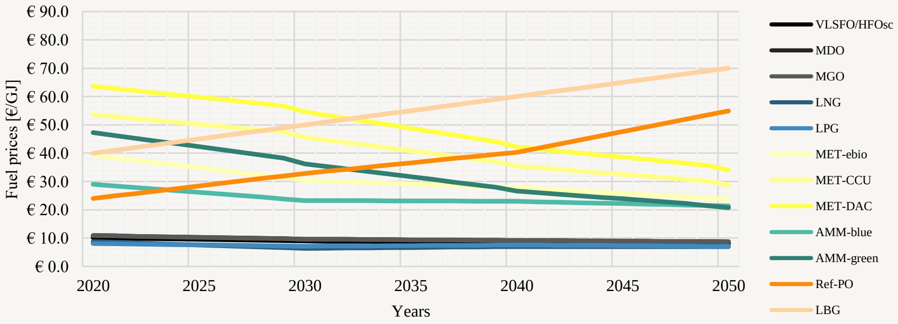


Figure 21: A visualization of marine fuel prices to shipping companies in €/GJ for RFNBO production location Dakhla

It is important to note that aside from the fuel prices for RFNBOs, other data remains constant across both scenarios. The following observations can be made when examining the data. Firstly, the RFNBOs produced in Dakhla come at significantly lower cost than Esbjerg, especially in the early years of production. Secondly, at no point do fossil fuels become less cost-effective compared to alternative fuels. Thirdly, an increasing trend is anticipated in the biofuels category. This is most likely due to growing competitive demand from other sectors.

To maintain the model's operational functionalities, fuel prices are averaged once a year, based on production costs, transport costs and a profit margin. This approach contrasts with real-world scenarios, where fuels are traded as commodities and their prices are tied to macro-economic forces and policy dynamics.

3.4 PROJECTING FLEET SIZE AND COMPOSITION

This section explains the modelling process of converting available data into average sized ships to use in modelling, assessing the current and future shipping demand as well as engine performance. All modelling was performed in Excel. The output of the Excel modelling i.e., the volume of shipping demand per year and category is used as an input variable for the SEAMAPS model. The data in this section is retrieved from the MRV database[36], IMO's Fourth Greenhouse Gas Study [19] and the MarE-fuel TCO publication [119] Parts of the methodology build on chapter two of the MarE-fuel ROADMAP publication [40].

3.4.1 2020 Fleet Size and Shipping Demand

3.4.1.1 Data cleaning

As mentioned in **Section 2.1.4.2**, the MRV database contains data on all shipping voyages from and to EEA ports. The database reports on fifteen different ship categories. These categories were grouped into five, following the report of the United Nations Conference on Trade and Development (**UNCTAD**): Bulk Carriers, Oil Tankers, Container Ships, General Cargo Ships and Other types [120]. **Table 8** shows the categorization of these ships.

Table 8: Number of ships in the monitored fleet categorized by UNCTAD categorization. [36 ,120]

Category	Ship type	Nr. Ships > 5,000GT, berthing at least once at EEA harbor, 2020 (pre-cleaning)	Using oil-based fuels	Using LNG
Bulk carriers	Bulk carrier	3213	3052	161
	Combination carrier	15	14	1
	Refrigerated cargo carrier	152	144	8
Oil tankers	Oil tanker	1920	1824	96
Container ships	Container ship	1826	1735	91
General cargo	Vehicle carrier	457	434	23
	ro-ro ship	243	231	12
	Container/Ro-Ro cargo ship	70	67	4
	General cargo ship	1219	1158	61
Other types	Gas carrier	345	328	17
	Chemical tanker	1333	1266	67
	LNG carrier	277	263	14
	Other ship types	126	120	6
	Passenger ship	109	104	5
	Ro-Pax ship	394	374	20

Amongst other indicators, the MRV dataset reports on technical efficiency, fuel consumption, CO_{2eq} emissions during intra-EEA voyages and CO_{2eq} emissions during extra-EEA voyages. Firstly, weights were assigned based on fuel consumption per category as shown in **Equation [14].**

$$w_{s,i} = \frac{f_s}{\sum_{i\in s} f_i} \qquad [14]$$

Here $\boldsymbol{w_s}$ is the weight of ship $\boldsymbol{i}$ in category $\boldsymbol{s}$, $\boldsymbol{f_s}$ is the fuel consumption of a ship in category $\boldsymbol{s}$ and $\boldsymbol{\sum_{i\in s} f_i}$ represents the sum of fuel consumption of all ships $\boldsymbol{i}$ in category $\boldsymbol{s}$.

Subsequently, the dataset was cleaned using the Interquartile Range method (IQR). This method was favored over methods that rely on mean and standard deviation as it is less affected extreme values [121]. This method was opted for since the MRV database contained more than several extreme values. Balancing data using weights both emphasizes the relative importance of larger ships over smaller ones and allows for better cleaning by reducing the discrepancy from outliers.

3.4.1.2 Fleet emissions

Now that the dataset was cleaned, the column in the MRV database reporting on CO_{2eq} emissions could be summed in order to get the fleet emissions. Consideration Was given to the consequence that excluding outliers would reduce cumulative emissions and fuel consumption in the results. This was addressed using a correction factor based on the verified total fleet emissions in 2020 [122]. This value was divided by the sum of the emissions in the cleaned dataset. The equations are:

$$CO_{2eq,TtW} = \sum_{i} \left(CO_{2eq,TtW,i}\right) \qquad [15]$$

$$CF_{CO_{2eq,TtW}} = \frac{CO_{2eq,TtW,2020}}{CO_{2eq,TtW}} = 1.277 \qquad [16]$$

Here, $\boldsymbol{CO_{2eq,TtW}}$ are the TtW emissions of the fleet in the cleaned database and $\boldsymbol{CO_{2eq,TtW,i}}$ represents the TtW emissions of a ship $\boldsymbol{i}$. $\boldsymbol{CO_{2eq,TtW,2020}}$ is the verified fleet TtW emissions for 2020 and $\boldsymbol{CF_{CO_{2eq,TtW}}}$ represents the correction factor based on TtW emissions.

As discussed in **Section 2.1.3.1**, FEUM requires GHG intensity reduction on a WtW basis. Therefore, the values in the dataset required a conversion. This was done by first assessing the average emission values of the fuel mix in 2020. **Table 9** shows the fuel mix in 2020, the energy content of each fuel and respective emission factors [88] [123]. Based on the respective fuel shares in the mix and the emission factors per fuel, a fleet average on both emissions and energy content could be calculated. The conversion factor from TtW to WtT is dividing the average WtT value for 2020 by the TtW value for that same year.

Table 9: Share of fuel consumed by the monitored fleet as well as their energy content and GHG intensity. [88] [123]

Category	Fuel share	Energy content [GJ/kg]	WTW emission factors [kgCO$_{2eq}$/GJ]	WTT emission factor [kgCO$_{2eq}$/GJ]	TTW emission factor [kgCO$_{2eq}$/GJ]
HFO	10.0%	39	88.5	9.6	78.9
VLSFO	65.0%	40.6	92.1	13.2	78.9
MGO	13.0%	42.7	90.8	14.4	76.4
MDO	7.0%	42	90.8	14.4	76.4
LNG	4.9%	48	85.7	18.5	67.2
LPG	0.1%	46.3	72.2	7.2	65.5
Average		**41.181**	**91.16**	**13.345**	**77.815**

The total WtW emissions per category, could then be calculated using **Equation [17]**. Subsequently the weighted average TtW emissions per ship type was calculated using **Equation [18]**.

$$CO_{2eq,WtW,s} = \sum_{i\in s} \left(CO_{2eq,TtW,s,i}\right) * CF_{CO_{2eq,TtW}} * EF_{CO_{2eq,WtW}} \qquad [17]$$

$$WA\_CO_{2eq,WtW,s} = \sum_{i\in s} \left(\mathrm{W}_{s,i} \times CO_{2eq,TtW,s,i}\right) * CF_{CO_{2eq,TtW}} * EF_{CO_{2eq,WtW}} \qquad [18]$$

Here, $\boldsymbol{CO_{2eq,WtW,s}}$ is the total WtW emissions per category $\boldsymbol{s}$ and $\boldsymbol{CO_{2eq,TtW,s,i}}$ represents the TtW emissions of a ship $\boldsymbol{i}$ in category $\boldsymbol{s}$. $\boldsymbol{CF_{CO_{2eq,TtW}}}$ represents the correction factor based on TtW emissions while $EF_{CO_{2eq,WtW}}$ is the share WtW/TtW share. $\mathrm{W}_{s,i}$ is the weight of ship $\boldsymbol{i}$ in category $\boldsymbol{s}$ based on emissions.

As mentioned in **Section 2.1.2**, FEUM makes a distinction between intra and extra EEA voyages. Ships on Intra-EEA voyages must comply 100% whereas extra EEA voyages require only 50% compliance. Therefore, it is important to know the share of shipping demand that are inter and extra EEA. As explained in **Section 2.1.4.2**, the MRV database reports on CO_{2eq} emissions based on this distinction. To calculate the total and weighted average emissions per voyage and ship category, **Equation [17]** and **Equation [18]** were used, altering only the total emissions column in the cleaned dataset to emissions per voyage type. The outcome is presented in **Table 10**:

Table 10: Calculated total WTW emissions per ship category and weighted average (W_A) WtW emissions categorized by voyage type.

Category	Total WtW emissions [t]	W_A WtW [t]	W_A intra EU WtW [t]	W_A extra EU WtW [t]
Oil tankers	26,150,047	17,901	4,693	13,202
Bulk carriers	20,880,689	7,264	1,904	5,357
General cargo	18,811,205	11,620	3,047	8,570
Container ships	58,635,371	48,787	12,791	35,981
Other types	27,281,391	9,325	2,445	6,877
Total	**151,758,702**	**15,053**	**3,946**	**11,102**

From this table it can be deduced that 26.2% of emissions occur during intra-EEA voyages versus 73.8% during extra EEA voyages. Henceforth, wherever a distinction is made between intra and extra-EEA voyages, the total value will be multiplied by either (0.262) or (1 - 0.262) to allocate it correctly.

3.4.1.3 Average ships and fuel consumption

For modelling purposes, the monitored fleet (i.e., the ships that need to report data to the MRV database) needs to be converted into average ships. This is done by dividing the total WtW emissions per category by the weighted average WtW emissions per category.

Besides ship type, the model categorizes by fuel type. The consumption shares per fuel of the 2020 monitored fleet depicted in **Table 9** is multiplied by the number of average vessels to return an array which distinguishes between both type and fuel. The result is depicted in **Table 11**:

Table 11: Nr of average sized ships categorized by ship category and type of fuel.

Category	# of average vessels	# powered by heavy fuel oils (HFO + VLSFO)	# powered by light fuel oils and distillates (MGO + MDO)	# powered by LNG
Tanker	1,461	1,096	292	55
Bulk	2,875	2,156	575	108
General cargo	1,619	1,214	324	61
Container	1,202	901	240	45
Other	2,926	2,194	585	110
Total	**10,082**	**7,561**	**2,016**	**378**

The total fuel consumption per category in 2020 was determined by summing the fuel consumption of ships ***i*** in category ***s***. The total weighted average consumption and weighted average consumption per voyage type were then calculated by dividing total fuel consumption per category by the number of average ships within that category. Both equations are depicted below.

$$F_s = \sum_{i \in s} (F_{s,i}) * CF_{CO_{2eq,TtW}} \qquad [19]$$

$$WA\_F_s = \frac{F_s}{\#\ average\ ships_s} \qquad [20]$$

Here, $\boldsymbol{F_s}$ is the total fuel consumption per category $\boldsymbol{s}$ and $\sum_{i\in s}(F_{s,i})$ is the summation of fuel consumption of ship $\boldsymbol{i}$ in category $\boldsymbol{s}$, corrected for data cleaning by correction factor $\boldsymbol{CF_{CO_{2eq,TtW}}}$. $\boldsymbol{WA\_F_s}$ represents the weighted average fuel consumption per category ***s.***

Notice how **Equation [19]** does not convert TtW to WtW emissions. In this case fuel consumption is calculated using direct emissions and fuel GHG intensity. This excludes the need to consider upstream emissions.

The weighted averages were multiplied by the emissions share of intra-EEA (26.2%) and extra-EEA (73.8%) voyages to categorize per voyage type. The fuel consumption was calculated in terms of energy by multiplying the total fuel consumption per category by the fuel mix energy content. The fuel consumption characteristics of the monitored fleet in 2020 can be found in **Table 12** below.

Table 12: Aggregated fuel consumption and per average sized ship, which is expressed per voyage and in both mass [t] and energy [GJ].

Category	Total Fuel consumption [t]	W_A fuel consumption [t]	W_A intra EU fuel consumption [t]	W_A extra EU fuel consumption [t]	Average fuel consumption per ship [GJ]
Oil tankers	7,089,084	4,853	1,272	3,579	199,848
Bulk carriers	5,661,337	1,969	516	1,453	81,106
General cargo	5,091,754	3,145	825	2,320	129,527
Container ships	15,972,779	13,290	3,484	9,801	547,292
Other types	7,494,630	2,562	672	1,889	105,492
Total / average	**41,309,583**	4,097	1,074	3,022	168,738

FEUM targets the 100% of fuel consumed during intra EEA voyages and 50% of the fuel used during extra EU voyages. To address this, the total amount of fuel consumed during extra EU voyages is multiplied by 50%. The share of fuel that falls within the scope of FEUM is 63.1%. The residual fuel is deemed beyond of the scope of this study, but clearly illustrates FEUM's significant tolerance to fossil fuels.

3.4.1.4 Shipping demand

The Energy Efficiency Design Index (**EEDI**) is a minimum energy efficiency level, per capacity mile. It dictates the maximum emissions per unit of work in $gCO_2/(t\cdot nm)$ for a ship, based on category, size and age [124]. The MRV database also reports on this metric. It can be used to calculate the amount of work each average ship of category ***s*** has performed in 2020. First the average technical efficiencies are tallied. For ships without an EEDI, the average of its category was assumed. The weighted average TtW emissions of category ***s*** were divided by the weighted average EEDI of the respective category. The equations are given below.

$$WA\_EEDI_s = \sum_{i\in s}(\mathrm{W}_{s,i} \times EEDI_{s,i}) \qquad [21]$$

$$TW_{av\_s,s} = \frac{CO_{2eq,TtW,s}}{WA\_EEDI_s} \qquad [22]$$

Here $\boldsymbol{WA\_EEDI_s}$ is the weighted average EEDI for ship type $\boldsymbol{s}$, $\boldsymbol{\mathrm{W}_{s,i}}$ is the weight based on emissions and $\boldsymbol{EEDI_{s,i}}$ is the EEDI of ship $\boldsymbol{i}$ in category $\boldsymbol{s}$. $\boldsymbol{TW_{av\_s,s}}$ represents the transport work of an average ship in category $\boldsymbol{s}$ in [Gt/nm] and $\boldsymbol{CO_{2eq,TtW,s}}$ is the total TtW emissions of category $\boldsymbol{s}$.

The transport work is described in the unit of gigatonne-nautical miles (gt·nm), with one gt·nm meaning the transport of 1 gigatonne load over one nautical mile (1.852 kilometers). Both fuel consumption and shipping demand are used as input data for the model.

3.4.1.5 *Ship age distribution*

Figure 22 shows the age distribution of the world fleet in 2018 and the average lifetime per category in [years]. Data was retrieved from ‘Shipping Market Review’ [125]. From the figure it becomes apparent that the distribution varies significantly per ship type. The number of ships exceeding the age of 25 is much higher for general cargo and for other ships compared to tankers, bulk carriers, and container ships. **Figure 23** shows the calculated distribution in starting year 2020.

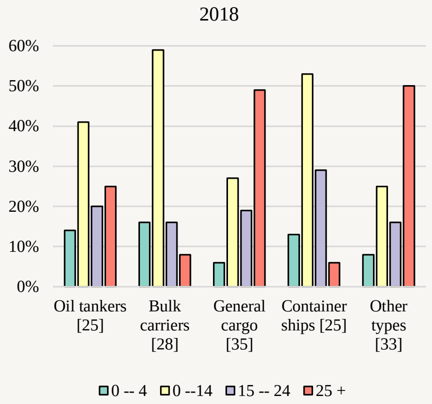


Figure 22: A visualization of the world fleet’s age distribution in 2018. [125]

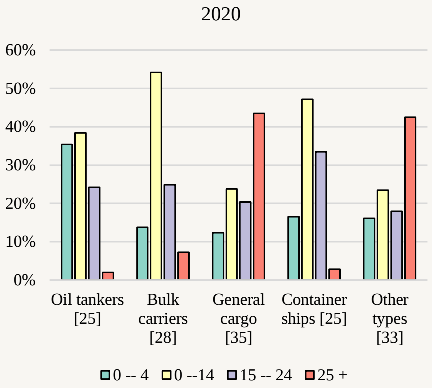


Figure 23: A visualization of the world fleet’s age distribution in 2020 with the scrapping if average lifetime is reached assumption.

It is assumed that once a ships age has exceeded the average lifetime of its category, it is immediately scrapped. E.g., based on this assumption one could conclude that none of the current fleet oil tankers remain in service after 2043. Similar calculations were made for other ship types. To model the decline of the existing fleet, a linear function is assumed between age buckets and no newly built ships are added, apart from those that are currently on order [29]. The decline of the current fleet of average ships is depicted in **Figure 24**. The existing fleet will serve as one of the model pillars. Based on this information, the model will estimate how many ships will need to be added to the stock to meet demand.

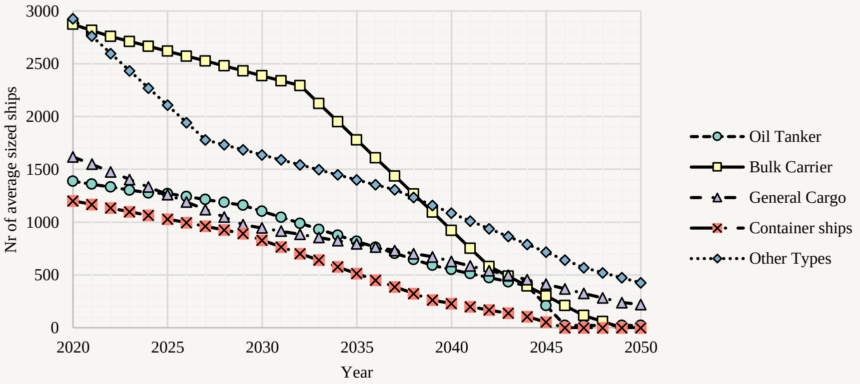


Figure 24: A visualization the number of average ships in the existing EEA fleet decreasing over time as more exceed their respective average total lifetime and excluding adage of new ships.

3.4.2 Engine Data

3.4.2.1 Fuel consumption

The fuel efficiency of ships is indicated by the category specific fuel consumption which is calculated using the following formula:

$$SFC_{f,s} = \frac{TW_s^{tot}}{FC_s^{tot}} \tag*{[23]}$$

Here $\boldsymbol{SFC_{f,s}}$ is the specific fuel consumption per category s and fuel f in [gt·nm/PJ]. $\boldsymbol{TW_s^{tot}}$ is the total work of category $\boldsymbol{s}$ in [gt·nm] and $\boldsymbol{FC_s^{tot}}$ is the total fuel consumption of category $\boldsymbol{s}$ in [PJ]. The table shows the outcome:

Table 13: Specific fuel consumption of average ships per ship type [gt·nm/PJ].

	Oil tanker	Bulk carrier	General cargo	Container ship	Other type
$SFC_{f,s}$ **[gt·nm/PJ]**	15.40	12.94	4.67	4.66	5..76

3.4.2.2 Average power

As the MRV database does not report on this, data on average engine power was adopted from literature. This engine power of average ships is displayed in the table below:

Table 14: Engine power in [MW] for average ships per category.[40]

	Oil tanker	Bulk carrier	General cargo	Container ship	Other type
Engine power [MW]	4.8	7.99	5.14	28.24	1.59

3.4.3 Total Cost of Ownership

Capital Expenditure (**CAPEX**) and Operational Expenditure (**OPEX**) input data used in this research were derived from literature [119]. The engine cost is multiplied by the average power to get the CAPEX displayed in the table below, which also displays the OPEX per category. The OPEX is assumed to be static across all engine types.

Table 15: CAPEX per engine type and fuel for average vessel per category. Bottom row reports on OPEX .[119]

Ship category		**Oil tanker**	**Bulk carrier**	**General cargo**	**Container ship**	**Other type**
Engine power [MW]		**4.8**	**8.0**	**5.1**	**28.2**	**1.6**
Main fuel	**Engine type**					
Fuel Oil	**ME-C**	15.0	18.8	15.0	70.3	5.6
LNG	**ME-GI**	18.9	24.4	18.9	79.7	7.5
LPG	**ME-LGIp**	18.3	23.1	18.3	76.6	6.9
Methanol	**ME-LGIm**	17.4	22.2	17.4	75.8	6.7
Ammonia	**ME-LGIa**	18.4	23.3	18.4	77.4	6.9
OPEX	**All engines/fuels**	2.1	2.5	2.1	3.3	0.9

3.4.4 Future fleet size and shipping demand

Data for the shipping demand for each vessel over time was retrieved from tables 73 and 74 of the IMO's fourth GHG study [19]. The organizations transport work projections based on SSP from 2020 to 2050 was adopted and extrapolating linearly to model future shipping demand for the EEA-operating fleet. This approach assumes that trends in the global shipping sector are directly applicable to the European shipping sector. This is an oversimplification as certain geographical markets may experience different levels of growth. The growth rate is most likely overestimated. [c]

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[c] The assumptions made in this section of methodology are listed in **Annex D**

3.5 OUTCOME INTERPRETATION

3.5.1 GHG Abatement Costs

GHG abatement cost is the cost of an intervention that will reduce greenhouse gas emissions by one tonne [126]. To calculates it one divides the additional costs (CAPEX + OPEX) by the avoided emissions, which returns the price per tonne of not emitted CO_{2eq}. The abatement costs were calculated for all scenarios, using the equation depicted below:

$$AC_{GHG} = \frac{\Delta Cost}{\Delta Q_{GHG}} \quad [24]$$

Here $\boldsymbol{AC_{GHG}}$ is the abatement cost in €/tCO_{2eq}, $\boldsymbol{\Delta Cost}$ is the additional cost of this scenario compared to the baseline in €. $\boldsymbol{\Delta Q_{GHG}}$ is the avoided mass of emissions compared to the baseline in t.

3.5.2 Sensitivity Analysis

To assess the effect of certain parameters and input variables on the outputted optimal fuel mix and thereby answering the fourth and final research questions, adjustments were made to certain parameters and input variables before executing a various model runs. The three parameters/input variables selected for this sensitivity analysis are listed in the **Table 16** below and were picked based on their perceived impact on the model. The table provides the name, function, and explanation of the parameter/input variable as well as the range of the upper and lower limit assessed. Two runs were performed per parameter/input variable: one for the lower value, and one for the upper value. All other parameters/input variables were kept constant.

Table 16: Parameters/input variables selected for the sensitivity analysis and their justification.

Name	Function	Explanation	Lower	Upper
Ramping Rate	Tuning parameter	The ramping rate in the SEAMAPS model determines at which speed installed capacity of ‘Bottleneck Technologies’ (i.e., electrolysers and CCS) can be added. In normal circumstances it is assumed to be 150%, meaning that every year, capacity can be increased to 150% of the total installed capacity a year prior. Seeing how the	- 50 percent point	+ 50 percent point
Specific Fuel Consumption	Input variable	Calculated in **Section 3.4.2,** the SFC is a measure of ship efficiency per category. Although FEUM sets targets for relative GHG reduction of fuels and excludes efficiency gains as compliance measures, it is still a very interesting input variable to consider. Energy efficiency plays a crucial role in the energy transition, as reducing energy required leads to lower fuel costs and emissions and vice versa.	- 20.0%	+ 20.0%
Fossil fuel prices	Input variable	Fossil fuels remain the most cost-effective fuel category throughout the observed time period. **Figure 20** and **Figure 21** show that costs per GJ for RFNBOs are significantly higher. Consequently, the model outputs the minimum RFNBOs required for FEUM compliance. Exploring the impact of fossil fuel prices on RFNBO demand and determining a threshold for overcompliance should be investigated.	- 50.0%	+ 400.0%

4. RESULTS

This chapter presents the results obtained over the course of this research. This chapter structured into four sub-chapters, each dedicated to answering a specific sub-question. In section 4.1, the outcomes of modelling the fleet are presented. These outcomes shed light into the evolution of the EEA-operating fleet from 2020 - 2050. In section 0, the focus shifts to evaluating the optimal fuel mix per scenario. This offers insights into which fuels could gain substantial market share in the future. In section **Error! Reference source not found.**, the emission profiles for each scenario are discussed, which reveals not only the emissions per year per scenario, but also the cost-effectiveness of emission-abatement per scenario. The chapter concludes in section 0 with a sensitivity analysis which assesses the difference in optimal fuel mix output as various parameters/input variables are altered. This structured approach aims to clearly communicate the multifaceted findings on fleet development, fuel optimization and GHG abatement costs within the context of FEUM.

4.1 PROJECTION FLEET SIZE AND COMPOSITION

4.1.1 Excel Modelling Outcome

The extrapolation of the IMO tables as explained in **Section 3.4.4** yields **Figure 25** and **Figure 26**, which depict the shipping demands per SSP, year and category in gt·nm. The sum of values x in year y equals the total demand.

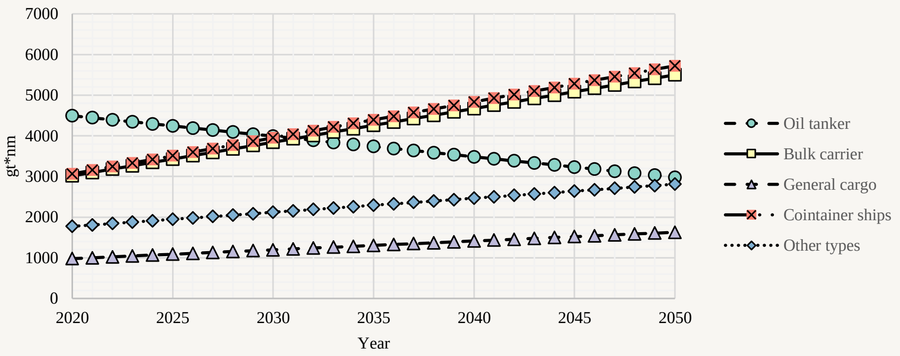

Figure 25: The shipping demand for the EEA-operating fleet under SSP1

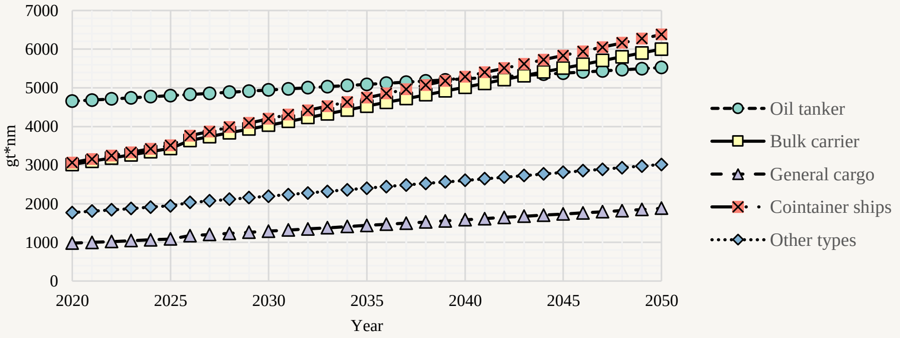

Figure 26: The shipping demand for the EEA-operating fleet under SSP5

When examining **Figure 25** and **Figure 26**, it becomes clear that demand for the EEA-operating fleet is poised to grow substantially in the coming decades. However, this growth is highly influenced by the SSP the world has opted for. Noticeable is the lower demand growth across all categories in SSP1 compared to SSP5.

Another noteworthy observation is the dynamics of the ‘Oil tanker’ category. This category experiences a significant reduction in size in SSP1, falling from roughly 4,500 gt·nm in 2020 to roughly 3,000 gt·nm in 2050. In contrast, the same group in SSP5 shows steady growth over the same period.

These trends are linked to the differences in GDP and population growth between SSP1 and SSP5. Additionally, the energy-intensive lifestyle promoted in SSP5 has a significant impact on energy imports. SSP1, which emphasizes prioritizing energy efficiency, requires less demand for fossil fuels. Consequently, the demand for category ‘Oil tankers’ reduces.

The largest observed demands for categories within the EEA-operating fleet in both SSPs are in the ‘Bulk carriers’ and ‘Container ships’. This is observation is further reinforced when examining the shipping share per category in **Figure 27**. Here the inner ring represents the relative share in shipping demand per sector in 2020. The outer ring represents the demand share per category in 2050. In 2050, ‘Bulk carriers’ and ‘Container ships’ combined account for a notable 60% in SSP1 and 54% in SSP5.

From this figure it becomes clear that SSP1 experiences a relative increase in the ‘Other type’ category. Conversely, despite an increase in demand for oil tankers in SSP5, the relative share of this category decreases by 10 percent points over the observed time period, indicating that in this SSP oil loses market share to other fuels.

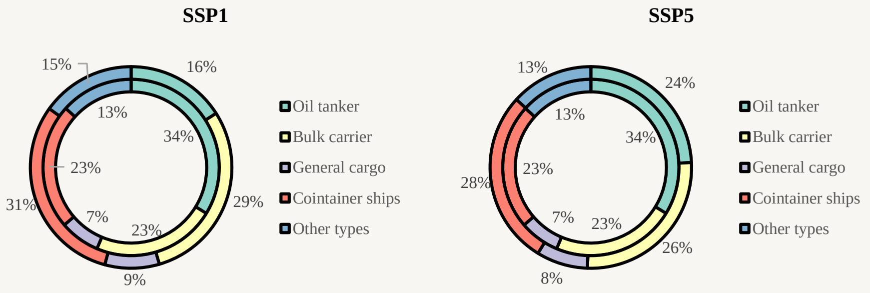

Figure 27: A visualization of the shipping demand covered by categories in SSP1 and SSP5 scenarios. The inner circle represents the starting year of 2020, the outer circle represents 2050.

Based on **Figure 26-29** it is not possible to draw conclusions on the rate of consumption within EEA member states. This is because the fleet is modelled in categories intra-EEA and extra-EEA. While this does tell us about global consumption trends, it is not clear which part originates from EEA and is exported to non-EEA countries, or the other way around. However, it is assumed that, that non-EEA countries experience the same SSP as EEA countries.

4.1.2 SEAMAPS Modelling Outcome

Figure 28 and **Figure 29** show the number of average sized ships needed per year and per category to comply with the shipping demand constrained outlined in **Table 5**. Perhaps unsurprisingly, the trends are similar to the ones seen in **Figure 25** and **Figure 26**. However, there exists a clear discrepancy between the demand for ships in a category and the amount of average sized ships in that category. This is due to different sizes of average ships within the categories; ‘Container ships’ tend to be much larger vessels than other type ships.

This is illustrated by the fact that in both SSP scenarios ‘Other type’ ships have the second highest number of operating vessels but service the second to lowest demand.

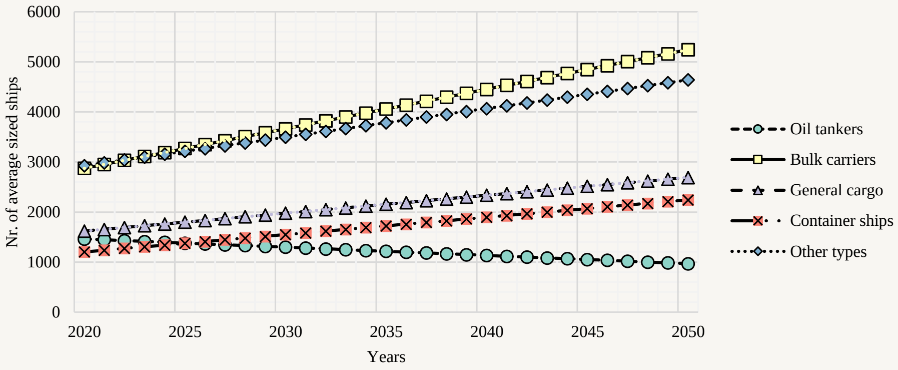

Figure 28: Modelling outcome: Number of average ships per category needed to service demand per year in SSP1.

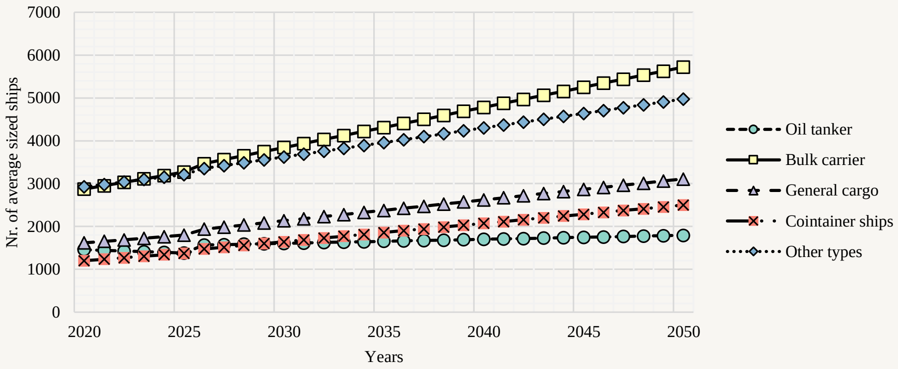

Figure 29: Modelling outcome: Number of average ships per category needed to service demand per year in SSP5.

The overall fleet grows significantly in numbers from now until 2050, with increases of 56.6% in SSP1 and 79.6% in SSP5. The total number of average ships increase from 10.1k in 15.8k in SSP1 and 18.1k in SSP5. The composition is set to change slightly. For instance, ‘Bulk carriers’ start to outnumber ‘Other types’ in the early 20’s, a lead which is further solidified by the steeper positive angle of the ‘Bulk carrier’ line. Once again, the major difference between SSPs is within the ‘Oil tanker’ category. SSP1 experiences a steady decline which results in a 30% decrease in oil tankers between 2020 and 2050. SSP5 sees a modest increase in this category. However, the rate of increase is lower the rest of the categories, and therefore the relative share is decreasing, implying that the significance of oil tankers decreases in both observed scenarios.

This loss of influence is further underscored by the fact that ‘Container ships’ overtake ‘Oil tankers’ in both scenarios. According to the outcome of this modelling exercise this will happen in 2026 for SSP1 and in 2030 in SSP5. Besides this change and the overtaking of ‘Other types’ by ‘Bulk carriers’, no positions are switched across categories and SSPs.

4.2 COST-MINIMIZED FUEL MIX

4.2.1 No FEUM

Figure 28 and **Figure 29** show the outcomes of the SEAMAPS model when it is not constrained by FEUM instruments. The model projects that the fuel requirements in 2050 will be 2680PJ in SSP1 and 3120PJ in SSP5; a difference of 450PJ, or roughly 17%. A notable sudden increase in fuel demand in SSP5 can be observed between 2025 and 2026. This is because the model operates under the assumption that the difference between SSPS will go into effect after 2025. The overall fuel demand in terms of PJ remains constant throughout each production location seeing as how it is dictated solely by SSP.

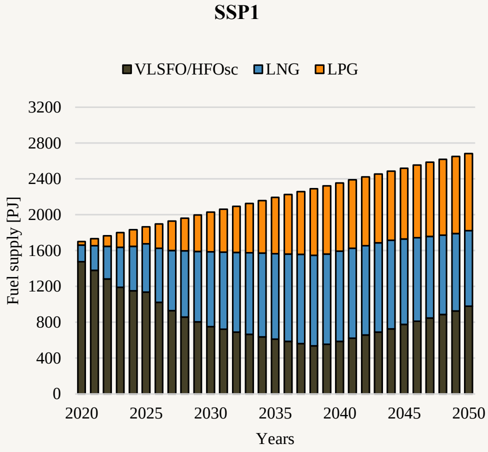

Figure 30: Optimal fuel mix if no FEUM constraints are introduced in **SSP1**

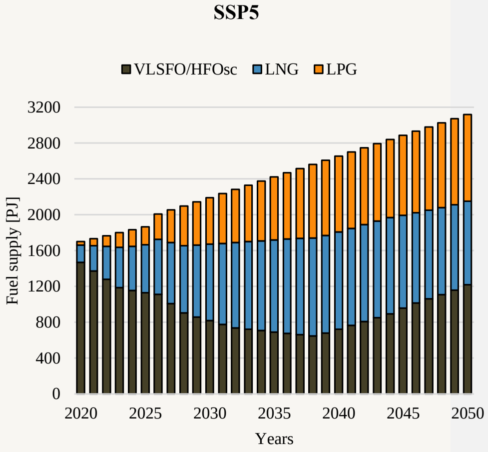

Figure 31: Optimal fuel mix if no FEUM constraints are introduced in **SSP1**

Both graphs unmistakably illustrate that a fuel transition is already taking place without FEUM. HFO/VLFSO has a dominant market share in 2020, which it swiftly loses to first LNG and subsequently to LPG over de following years. The lowest volume of HFO/VLFSO consumed according to the outcomes will be in 2038 for both SSPs. Following this year, the share is projected to gradually increase until it becomes the dominant fuel again in 2049 for SSP1 and a few years earlier in 2046 in SSP5.

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LNG gains in popularity quickly between 2020 and 2035 as it peaks in 2038 in both SSPs, remaining a coveted fuel after its peak. Perhaps a surprising ‘winner’ in the no FEUM scenarios is LPG, a fuel which is currently not dominantly represented in the fuel mix. As mentioned in **Section 2.5.1.3** it does boast some advantages compared to LNG despite being slightly more expensive. These advantages include less engine slip, lower cost of propulsion system and the easier fuel handling. The latter, not being part of this modelling exercise.
Unsurprisingly, no low carbon fuels are adopted in these pathways.

The shift away from VLSFO/HFO could be motivated by the expected cost competitiveness of LNG and LPG, in combination with the current order book of LNG powered vessels flooding the market after their construction. As mentioned in **Section 2.5.1.3**, nearly half of vessels on order will be equipped with DF engines, compatible with LNG. Despite the expected price drop in both LNG and LPG, VLSFO/HFO persists. In this scenario, shipping companies only have to minimize for costs and will therefore opt for the cheapest fuel and the cheapest engine. This means that a slow return to SF engines and VLSFO/HFO could be expected. Finally, all DF engines need a liquid pilot fuel. This means that if unregulated VLSFO/HFO would never go away even with DF engines.

4.2.2 Esbjerg

The outcomes when introducing FEUM constraints reveal significant impacts in the maritime fuel mix. The total fuel requirements per SSP remain constant. However, FEUM brings about significant transformation in the way this demand is met. **Figure 32** and **Figure 33** show the optimal fuel mix if RFNBOs were produced within the EU at the Esbjerg location.

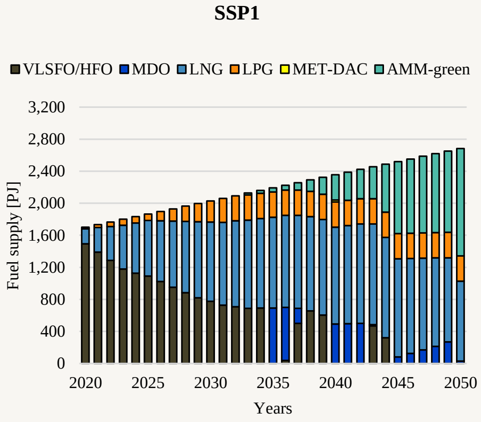
SSP1

Figure 32: Optimal fuel mix under FEUM in **Esbjerg_SSP1** scenario

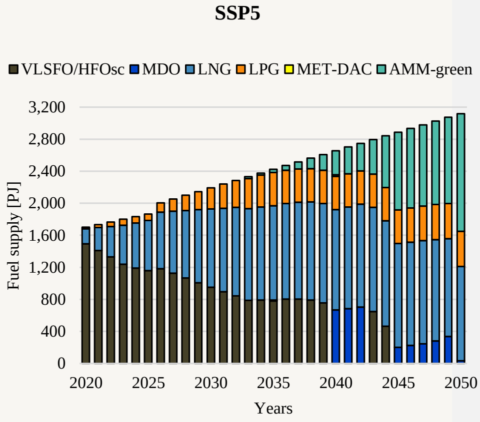
SSP5

Figure 33: Optimal fuel mix under FEUM in **Esbjerg_SSP5** scenario

Initially, there is a continuation of the previously observed trend towards LNG. This is to be expected as LNG is a relatively cheap fuel and the significant order book for this category. This growth is at the expense of VLSFO/HFO, which is phased out rather quickly by the model as a result of FEUM constraints.

A notable outcome is that the final year of VLSFO/HFO will be in 2045. As mentioned in section, this is under the assumption that in 2040 all pilot fuel will be transitioned to DME by 2040. Interestingly enough, the model solves for substituting VLSFO/HFO with MDO in some years. It can do this since it was assumed in **Section 2.3.2** that DF engines allow for fuel switching within the lifetime of a vessel. In reality, it is unlikely that a year-on-year shift as sudden and as big as this happen, since the bunkering industry most likely does not have reserves in the order of several hundreds of PJ of a fuel that has previously not been popular. This underscores the importance of recognizing the model's limitations and assumptions.

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The primary objectives of FEUM legislation, namely reducing GHG intensity and stimulating the uptake of RFNBOs are achieved in these outcomes. Both SSPs experience spectacular uptake of green NH_3, which is expected to quickly gain market share post 2035. For both SSPs the 1% uptake by market forces is not met, which triggers the 2% sub target in 2034. This jumpstarts demand for green NH_3, which interestingly enough is more profound for SSP1 than for SSP5 in the early years. This could have to do with the fact that the model operates on perfect foresight and therefore knows it has enough time to catch up to meet the reduction targets. SSP5 eventually does catch up and overtakes SSP1 in green NH_3 production in terms of energy in 2043.

Another striking observation is the reduced role of LPG in comparison with the no FEUM scenario. This could be a direct result from the increased demand for AMM-green. Outlined in **Section 2.6**, DF engines need one liquid and one gaseous fuel. Seeing as how ships bunker NH3 under FEUM, which is a gaseous fuel, the demand for LPG diminishes as it is also a gaseous fuel.

4.2.3 Dakhla

Figure 34 and **Figure 35** show the optimized fuel mix if RFNBOs would be produced in Dakhla. It becomes clear the difference in production location, inside or outside the EEA yields little difference in RFNBO uptake, as the trends observed in **Figure 33** and **Figure 34** are echoed. All production location scenarios experience a slow uptake of NH_3 until 2039 which accelerates quickly post 2040.

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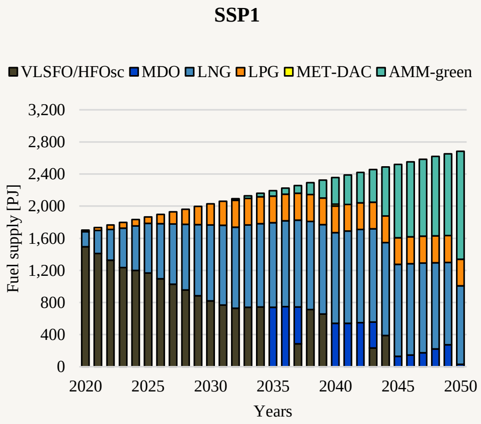

Figure 34: Optimal fuel mix under FEUM in **Dakhla_SSP1** scenario

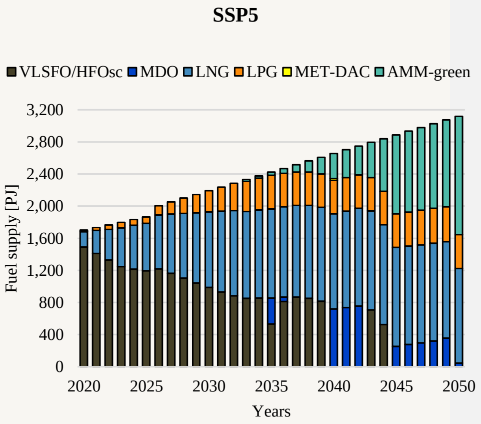

Figure 35: Optimal fuel mix under FEUM in **Dakhla_SSP5** scenario

This acceleration is due to two principles working together at opposite ends. First RFNBO producers can tap into the grid as this is now low carbon enough to meet the 70% GHG reduction standard outlined in **Section 2.2**. Additionally, reduction targets before 2040 are quite loose, maxing at 13.5% in 2035-2039 period. According to the outcome of the model these earlier reduction targets can most cost-effectively be covered by switching to gaseous fuels such as LNG and LPG. In 2040 the reduction target jumps to 31%, a number which doubles 5 years later. Now RFNBOs have to be introduced to meet this constraint.

Due to the modelled uptake for RFNBOs being quite late in the observed time period, the prices of RFNBOs produced in different locations have started to level out and are expected to continue to do so until at least 2050. However, throughout the duration of the model, Dakhla remains the cheaper location for RFNBO production. This results in a slightly higher uptake of green NH_3 in Dakhla scenarios compared to the Esbjerg scenario. This is most noticeable in the early years. For instance, there is 4.7% more NH_3 demand in both Dakhla scenarios in 2040 compared to the Esbjerg scenarios.

A large surprise is that at no point in both SSPs the model has opted for PS methanol (MET-PS), indicating it a clear ‘loser’ under this set of assumptions. However, interestingly enough a speck of yellow appears in 2040 for both SSPs and both production locations. This MET-DAC category represents CH_3OH produced using DAC technology and is the most expensive fuel the model can opt for. This implies a shortage of NH_3 production capacity in 2040.

Beyond RFNBO uptake, the outcomes of this model highlight the permissible fossil fuel consumption under FEUM legislation. Despite the mandated 80% GHG intensity reduction by 2050, the outcomes show an alternative fuel uptake of ~50%. In SSP1, fossil fuel consumption declines with 300PJ, or ~18%, whereas SSP5 virtually exhibits no fossil fuel consumption reduction. These less-than-optimal results are a product of substantial sectorial growth and FEUM’s mandate, which is too lenient to significantly reduce the sector’s GHG emissions by 2050.

4.3 GHG ABATEMENT COSTS

This section discusses the outcome of SEAMAPS modelling in terms of emissions and the price tag associated with the fuel transition for each scenario. First, the focus is on emissions per scenario, distinguishing being TtW and WtT emissions. Subsequently, the attention is directed towards fuel associated costs. Finally, the GHG abatement costs associated with each scenario are presented.

4.3.1 Emissions

Figure 36 shows the WtW emissions for al scenarios over time. The It is clear that there exist large differences between the annual emissions in SSP1 and SSP5. However, in terms of emissions little difference exist between the RFNBO production locations Esbjerg and Dakhla. Small differences can be observed in the early years which have to do with the cost-benefit of Dakhla production. However, the share of RFNBO in these early years is relatively insignificant and therefore the effect on GHG emissions is limited. The variance is reduced to nothing post 2040. This is why it looks like there are only two lines, while in reality one is beneath the other.

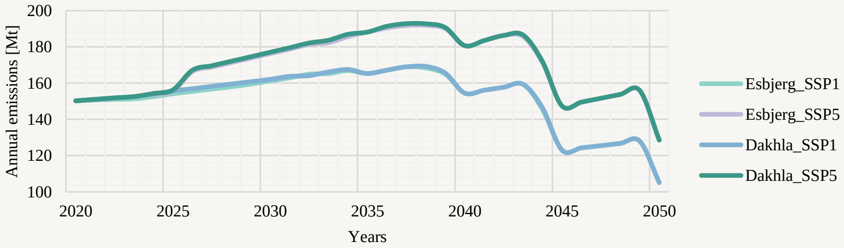

Figure 36: Absolute sector GHG emission trajectory under FEUM, zoomed in

The intentional omission of values below one hundred on the y-axis in **Figure 36** serves an illustrative purpose. When it is extended to zero the complete picture emerges: By 2050, emissions experience an approximate 1/3rd reduction in both SSP1 scenarios, while only marginal decreases can de observed in SSP5 scenarios.

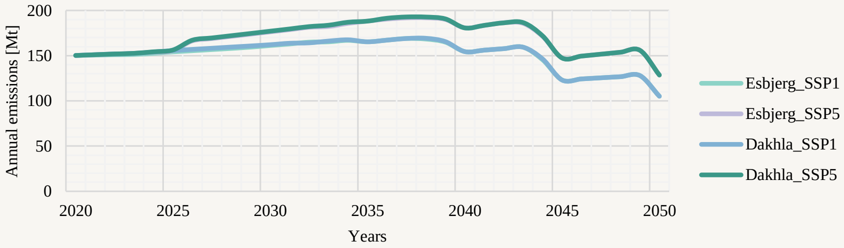

Figure 37: Absolute sector GHG emission trajectory under FEUM

Given consistent GHG emissions across RFNBO production locations, individual assessments are deemed irrelevant. Instead, focus is directed towards the differences between SSP1 and SSP5, illustrated by **Figure 38** and **Figure 39**.

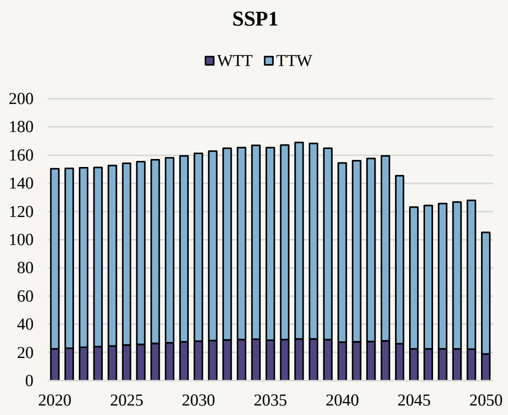

Figure 38: Absolute sector GHG emission trajectory under FEUM in **SSP1** divided by emission scope

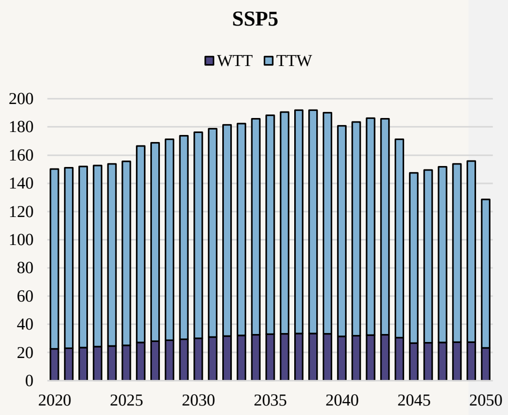

Figure 39: Absolute sector GHG emission trajectory under FEUM in **SSP5** divided by emission scope

These outcomes clearly show that GHG emissions from the EEA-operating fleet will continue to increase for both SSPs until the late 30's. In SSP1 the emissions peak is one year later to the peak in SSP5, the latter being in 2038. As expected, the annual volume of GHG emissions is much higher in SSP5 than in SSP1. This wedge in outcomes keeps increasing as both sectors develop separately, the largest variance is in 2049 in which year SSP5 emits 28Mt CO_{2eq} more compared to SSP1. In terms of cumulative emissions, SSP5 emits 550Mt CO_{2eq} more than SSP1 during the observed time period.

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From 2040 onwards, the effects of FEUM become clearer for both SSPs as the five-year intervals of reduction are reflected in the figures. In 2040, a 31% GHG intensity reduction target is to be met, which promises a sudden decrease in emissions. However, in the years after 2040 and before the next reduction targets, absolute emissions quickly build as the sector continues growing and the next reduction target is still five years out.

The model predicts that in 2050 emissions will be 105Mt CO_{2eq} in SSP1 and 128Mt CO_{2eq} in SSP5. This is a reduction of 30.1% and 14.4% respectively compared to the base year 2020. Underscoring the difficulty of decarbonizing a growing sector. If the sector remained exactly as it was in the base year, it would emit 75Mt CO_{2eq} or a reduction in absolute emissions of ~50% in 2050.

The relation between WtT and TtW emissions per SSP is depicted in **Figure 40**. From it, it becomes clear that the share of WtT emissions will increase steadily. This has two reasons. First of all, gaseous fuels such as LNG and LPG have higher upstream emissions and lower direct emissions as seen in **Table 2**. In addition, RFNBOs are considered to have very little emissions, therefore amplifying the effect of other fuels.

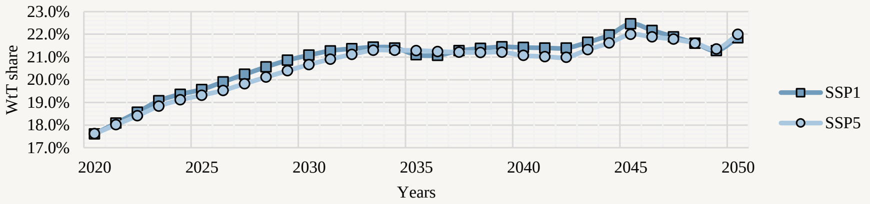

Figure 40: The share of WtT emissions in the total annual emissions

4.3.2 Fuel Associated Costs Premium

As mentioned in **Section 2.3.2.1**, the total fuel associated costs to shipping companies is a combination of fleet related costs, i.e., engine technology (CAPEX) and fuel costs (OPEX). **Figure 41** shows the fuel associated costs premium to shipping companies under FEUM in the Esbjerg_SSP1 scenario expressed in M€ (2019). The figure shows the difference with the unconstrained model run shown in **Figure 30**.

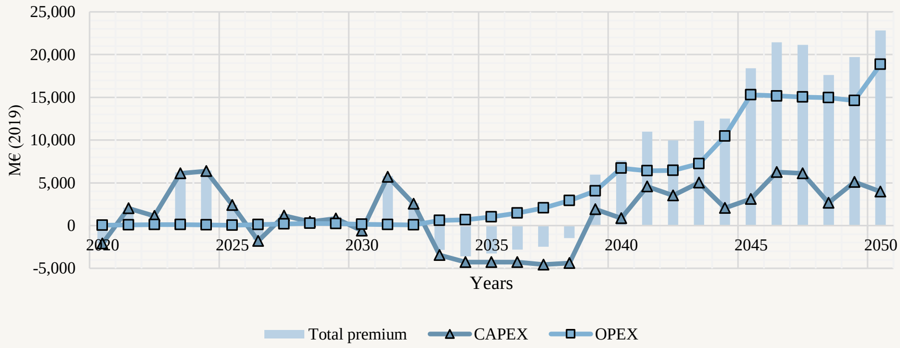

Figure 41: Cost premium to shipping companies under FEUM in **Esbjerg_SSP1** scenario

When inspecting the 'OPEX' series, it becomes clear that fuel associated costs are identical to the unconstraint scenario until 2033, which is one year before the issued 2% RFNBO sub-target. In this year a slight increase in costs can be observed. The model started production capacity in 2033 due to technology scaling constraints, and otherwise missing the 2% RFNBO sub target. Fuel cost premium rises steadily to ~€4bn p.a. in 2039, after which costs increase steeply. In 10 years, these more than triple from €6.7bn p.a. in 2040 to €22.8bn p.a. in 2050. The five-year increments of FEUM legislation targets are clearly represented in the fuel costs pattern.

A less discernable pattern emerges when the 'CAPEX' series is observed. From it, it becomes evident that the model has used different approaches to solve over time. Until 2032, the Esbjerg_SSP1 run makes more investments into dual fuel engines, which can be run on less GHG intensive fuels like LNG or LPG thereby meeting FEUM compliance targets until 2039, as outlined in **Figure 6**. Then there is a gully where more is spent on engine technology in the unconstrained run. From 2038 the Esbjerg_SSP1 run invests significantly more in engine technology compared to the unconstrained run. During the observed time period the average extra spending on engine technology is €1.4bn p.a.

Looking at the total fuel associated costs premium to shipping companies in Esbjerg_SSP1 under FEUM, it becomes clear that there is a significant divide between pre 2040 and post 2040. On average the total premium costs are €0.8bn p.a. before 2040 and €15.9bn p.a. post 2040, underscoring the exponential nature of these outcomes. On average the premium fuel associated costs to shipping companies is €6.1bn p.a. in this scenario, totaling at cumulative costs of €189.8bn.

Figure 42 shows the fuel associated costs premium to shipping companies under FEUM in the Dakhla_SSP1scenario expressed in M€ (2019). The trends in the 'OPEX' data series from **Figure 41** are echoed. Incremental increases per five-year periods are observed with slight but immediate drops between target years. This is best seen between 2040 and 2045, where there is a decrease a year after stricter regulations i.e., 2041, and costs start to increase again around 2043 due to scaling requirements. Then in the new target year 2045, another peak is observed.

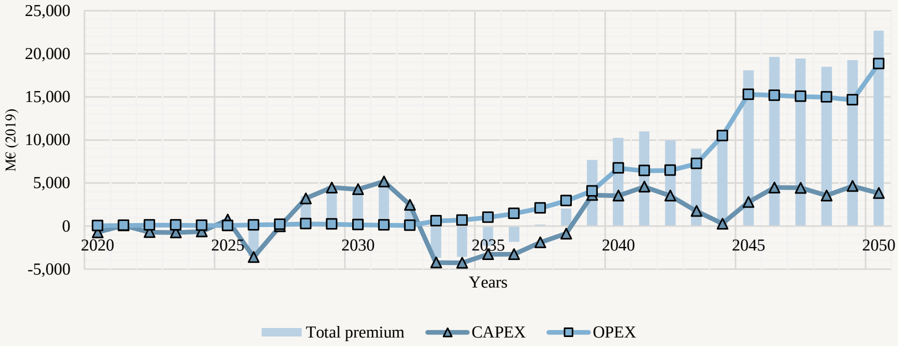

Figure 42: Cost premium to shipping companies under FEUM in **Dakhla_SSP1** scenario

The CAPEX strategy varies slightly if RFNBOs would be produced in Dakhla. At first, this run does not deviate from the unconstrained scenario much, meaning roughly the same engines are technologies are invested in. From 2027 to 2032 there is an increase in CAPEX compared to the unconstrained model. Then costs plummet in the mid ‘2030s and increase again around 2039, much like in the Esbjerg_SSP1 scenario. Although compared to it the average engine cost premium sits a little lower at €1.2bn p.a. From **Figure 45** it becomes clear that this scenario uses less LNG which is the most expensive engine type.

The average total premium costs to shipping companies under FEUM in this scenario sit at €5.9bn p.a. and is slightly less expensive compared to the Esbjerg scenario. The averaged difference between the two scenarios is €211M p.a. or €6.5bn during the observed time period.

Figure 43 shows the fuel associated costs premium to shipping companies under FEUM in the Esbjerg_SSP5 scenario expressed in M€ (2019). The figure shows the difference with the unconstrained model run shown in **Figure 31.** Although this scenario produces more RFNBOs in order comply with FEUM targets, the fuel costs premium in this scenario is comparable with the SSP1 scenarios. This has to do with both economies of scale for electrolysers and more VLSFO/HFO in the mix as becomes clear from figure **Figure 45.**

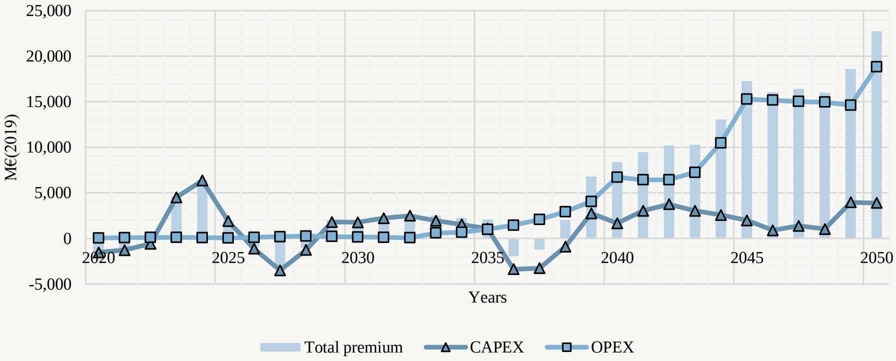

Figure 43: Cost premium to shipping companies under FEUM in **Esbjerg_SSP5** scenario

Compared to Esbjerg_SSP1 the costs for Esbjerg_SSP5 are more spread out over the observed time period. Pre 2040, the average total costs premium is €1.3bn p.a. (compared to €0.8bn). and post 2040 it is €14.4bn p.a. (compared to €15.9bn). Additionally, the total cost premium is slightly lower at €184bn.

Figure 44 shows the fuel associated costs premium to shipping companies under FEUM in the Dakhla_SSP5 scenario expressed in M€ (2019). Again, the 'OPEX' data series show a similar pattern to all other runs where FEUM constraints are active. The 'CAPEX' series shows resemblance to the Esbjerg_SSP5 scenario. There are small dips below the unconstraint model run in 2027 and 2037. This is the only scenario where investment in engines dips below the unconstraint model after 2040. The reason for this is most likely more investments early on.

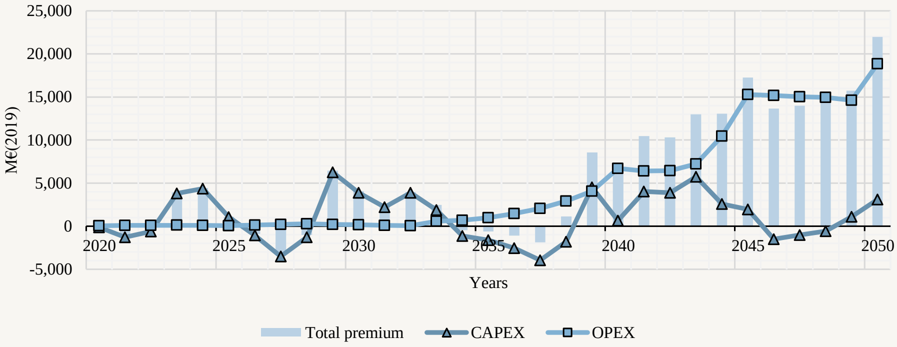

Figure 44: Cost premium to shipping companies under FEUM in **Dakhla_SSP5** scenario

Compared to Dakhla_SSP1 this scenario also has a better spread with €1.4bn p.a. (compared to €0.7bn) before 2040 and €13.7bn p.a. (compared to €15.3 bn) after 2040. Compared to all scenarios with FEUM constraints, Dakhla_SSP5 is the most cost-effective scenario with an averaged costs premium of €5.8bn p.a. and a total price tag of €178.6bn.

The total fuel associated costs in 2020 were modelled to be €32.6bn, which is within the range of the gross value added of the EEA operating fleet, which was €29.5bn in that same year [127]. In the unconstrained scenarios the annual fuel associated costs range from €30.0bn for SSP1 to €34.3bn for SSP5 in 2050. When introducing FEUM, the fuel associated cost premium to shipping companies is projected to swell to more than €20bn annually by the end of the observed time period across all scenarios. In 2050, this is a cost increase of 71% in the least cost-effective scenario (Esbjerg_SSP1) and an increase of 64% most cost-effective scenario (Dakhla_SSP5). However, costs are likely further balloon escalation post 2050, as deep decarbonization is often most expensive.

The increased fuel costs will ripple throughout global supply chains, affecting trade flows, and ultimately impacting consumer prices. It is therefore imperative to also include other cost-effective solutions such as energy efficiency gains, operational gains, and wind power, to reduce the amount of energy required for these movements in the first place.

4.3.3 GHG Abatement Costs

Figure 45 depicts the GHG abatement costs per scenario, which is an indication of cost-effectiveness of GHG reduction. It is calculated using the methodology outlined in **Section 3.5.1**. The results are presented per scenario accompanied by the fuel mix composition across the observed time period.

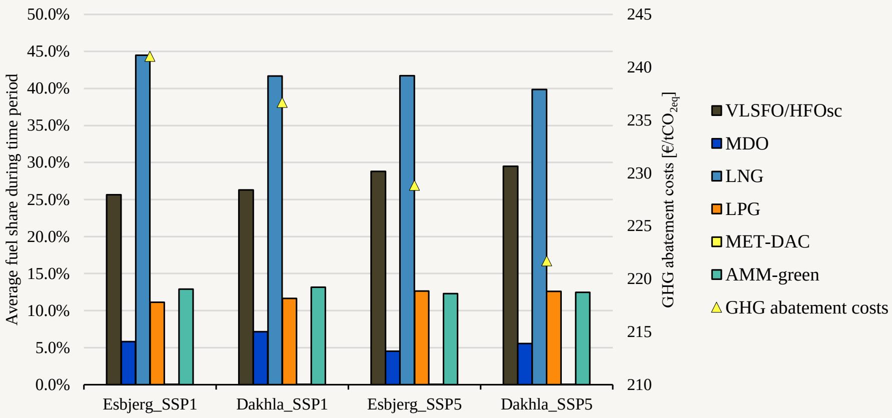

Figure 45: GHG abatement costs per scenario in €/tCO_{2eq}

From it, a downwards trend can be discerned when moving up in scenarios. The GHG abatement costs range from €241.0/tCO_{2eq} in Esbjerg_SSP1 to €221.7/tCO_{2eq} in Dakhla_SSP5. To put this into perspective, the global average GHG abatement costs of wind power was €27.1/tCO_{2eq} in 2020 [128]. In terms of removing atmospheric GHG, this measure is therefore roughly 8-9 times more expensive than wind power.

The clustered columns in **Figure 45** are the cumulative fuel shares depicted in the figures in **Section 4.2.** What is striking is that the relative share of RFNBOs remains static across scenarios, indicating that in SSP5 more RFNBOs are produced on an absolute level, but not relatively. As concluded in **Section** Error! Reference source not found., the enjoyed economies of scale experienced when producing RFNBOs in SSP5 more or less negate the extra fuel costs, making the costs premium for RFNBOs equally high in both SSP1 and SSP5. The cost difference therefore predominantly lies in other fuels. As can be observed, SSP5 uses relatively more VLSFO/HFO than SSP1 scenarios and less LNG. SSP5 scenarios have on average 1.2% more LPG in the fuel mix compared to SSP1 scenarios.

Overall, the SSP1 scenarios are less cost-effective in terms of GHG abatement costs compared to the SSP5 scenarios, which is unsurprising as they have less absolute emission reduction and higher costs premiums. However, in terms of cumulative emissions across the observed time period, the SSP1 scenarios emit on average roughly 500Mt CO_{2eq} less than the SSP5 scenarios.

4.4 SENSITIVITY ANALYSIS

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The sensitivity analysis performed assesses the impact of key assumptions, parameters, and input variables on the optimal fuel mix, and by extension the RFNBO uptake, WtW GHG emissions and fuel associated costs premium. The results are categorized by the assumption, parameter or input variable altered and explained per scenario.

4.4.1 Ramping Rate

The ramping rate in the SEAMAPS model determines at which speed installed capacity of 'Bottleneck Technologies' (i.e., electrolysers and CCS) can be added. In normal circumstances it is assumed to be 150%, meaning that every year, capacity can be maximally increased by a factor 1.5 compared to the total installed capacity a year prior.

Figure 46 and **Figure 47** show the sensitivity of the model's outcomes if the ramping rate assumption is altered over a range of -25 percent points (**p.p.**) to +50 p.p. For simplicity's sake, the sensitivity analysis has only been carried out on the Esbjerg scenarios.

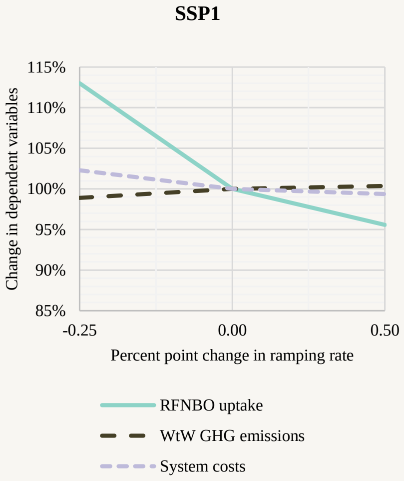

Figure 46: Change in dependent variables as a result of change in ramping rate in **SSP1**

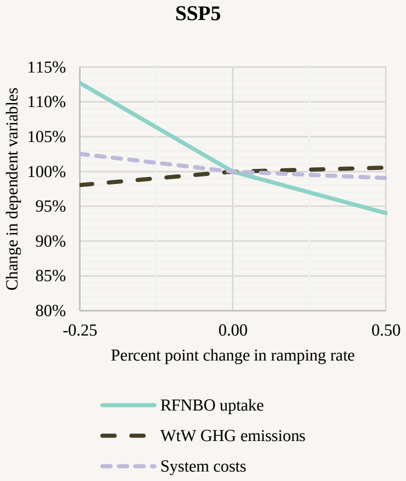

Figure 47: Change in dependent variables as a result of change in ramping rate in **SSP5**

The most striking observation that can be made from these figures is that a lower ramping rate results in more RFNBO uptake than an increased ramping rate. This can be attributed to the model's ability to operates with perfect foresight. This means it knows it can start later with the increasing production capacity, if it has a better ability to scale the production capacity. This in turn results in slightly higher emissions in high growth rate scenarios, as RFNBO production is postponed, and cheap fossil fuels are consumed for longer. This results in relatively lower fuel associated costs premium for these scenarios.

A growth rate of -50 p.p. was excluded from **Figure 46** and **Figure 47** as this caused the model to fail. This ramping rate proved to be too low to successfully meet both fuel demands and GHG reduction targets set by FEUM. This indicates that RFNBO production capacity needs to be able to increase to at least by 15% year-on-year in order to solve.

Figure 48 shows the fuel mix plotted over time for each model run performed in this part of the sensitivity analysis. If the ramping rate is increased by 50 p.p. less RFNBO uptake can be observed in the 2030s when compared to **Figure 32** and **Figure 33** with the 2% constraint just barely being met. As suggested earlier the model 'catches up', indicated by the total RFNBO volume in 2050 being the same as in the original optimal fuel mixes. No other trends appear. This is rather unsurprising as ramping rate does not affect RFNBO costs.

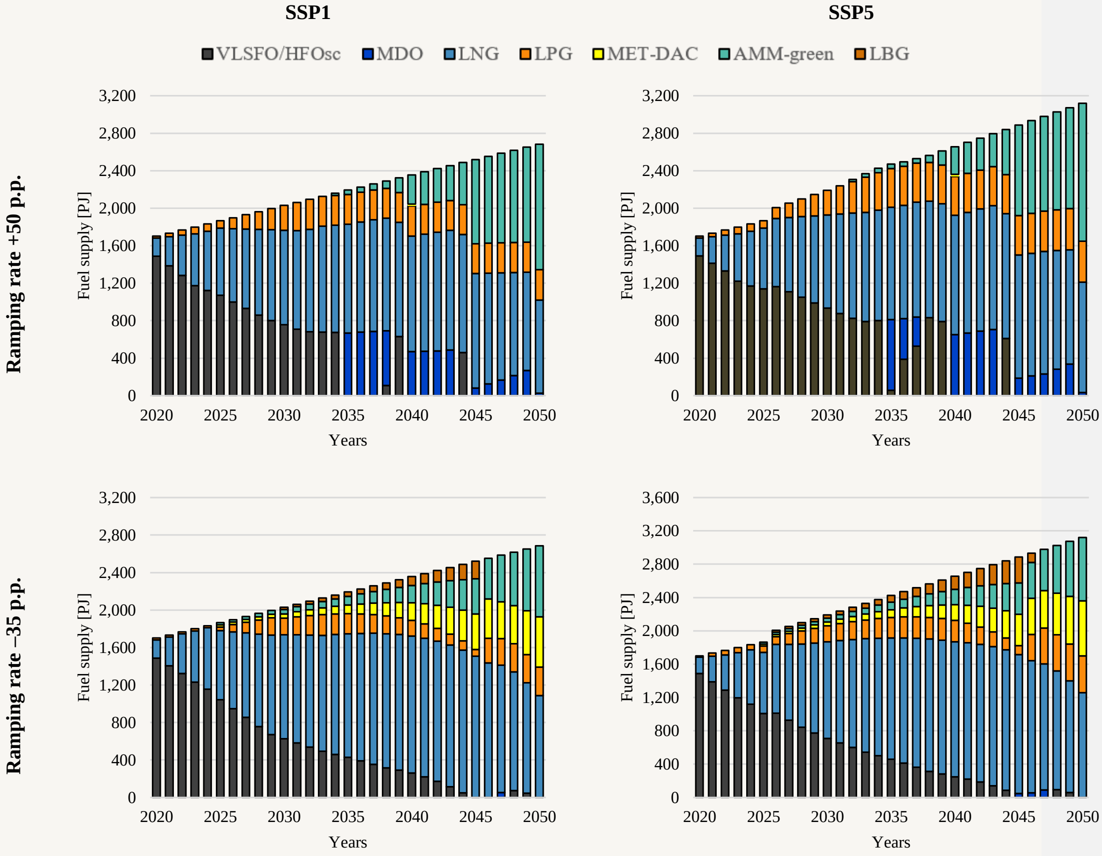

Figure 48: The impact of altering bottleneck technology ramping rates on the optimal fuel mix per SSP

Anything below -35p.p. of the conventional ramping rate and the model will opt for the gap fuel. This is a non-existing 'magic fuel' which has zero emissions but comes at a cost of roughly fifteen times the NH_3 price. The model can still solve properly at a ramping rate of 115% as becomes clear from the bottom row of these figures. These are the first outcomes where more than two alternative fuels are required to meet the demand. It becomes clear that due to scaling issues, LBG has to play a significant role in order to meet the FEUM targets. This is at the expense of LPG, the demand of which is clearly decreased in 2045. Post 2046 there is no LBG in the mix due to a combination of it becoming too expensive and a matured RFNBO production capacity. Additionally, CH_3OH plays a far more significant role than in other scenarios and VLSFO/HFO is phased out much quicker due to difficulties meeting the target.

4.4.2 Specific Fuel Consumption

Calculated in **Section 3.4.2,** the Specific Fuel Consumption (**SFC**) is expressed in gt*nm/PJ and is therefore a measure of ship efficiency. It was calculated for each ship type. Although FEUM sets targets for relative GHG reduction of fuels and excludes efficiency gains as compliance measures, it is still a very interesting input variable to consider. Energy efficiency plays a crucial role in the energy transition, as reducing energy required leads to lower fuel costs and emissions and vice versa.

Figure 49 and **Figure 50** show the sensitivity of the model's outcomes if the SFC is altered over a range of -20% to +20 % For simplicity's sake, the sensitivity analysis has only been carried out on the Esbjerg scenarios.

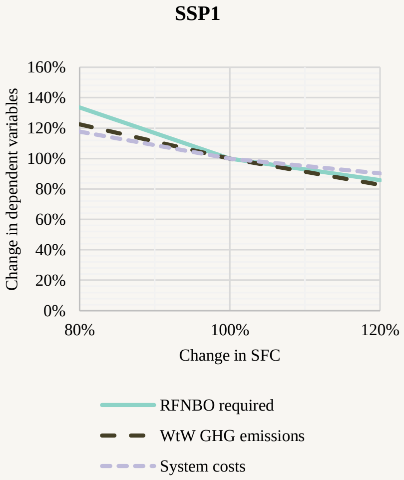

Figure 49: Change in dependent variables as a result of change in specific fuel consumption in **SSP1**

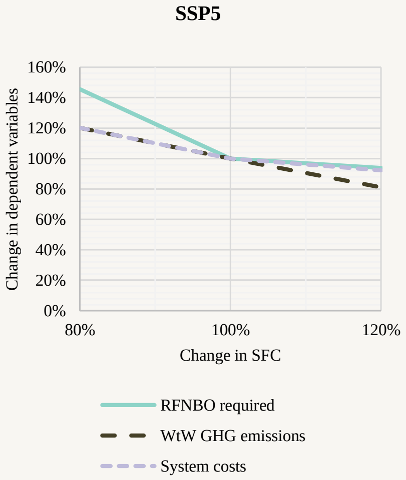

Figure 50: Change in dependent variables as a result of change in specific fuel consumption in **SSP5**

From these figures it becomes clear how much more RFNBOs are required if ship efficiency were to drop by 20%. Over the observed period the increase would be 34% for SSP1 and 46% for SSP5, resulting in fuel associated costs to increase by 20%. This would mean 20% on top of the >€20bn fuel associated cost premium in 2050 calculated in **Section** Error! Reference source not found..

Conversely, increasing ship efficiency reduces the volume of RFNBOs required and with it, the fuel associated costs and absolute emissions. Diminishing returns can be observed in **Figure 49:** Change in *dependent variables* as a result of change in *specific fuel consumption in* **SSP1** as a 20% increase in ship efficiency reduces total system costs and absolute GHG emissions by 10% and 17% respectively, compared to a 18% and 22% respective increase when ship efficiency is decreased.

SSP5 shows more return on energy efficiency in terms of absolute emissions, as 19% reduction is achieved this way compared to no SFC gain. Fuel associated costs and RFNBO uptake are less sensitive to change with 8% and 6% reductions respectively.

Figure 51 shows the fuel mix plotted over time for each model run performed in this part of the sensitivity analysis. As a result of altering the SFC, only minor changes appear in the fuel shares within optimal fuel supply. NH_3 still proves to be the dominant RFNBO and VLSFO/HFO is substituted by LNG over time.

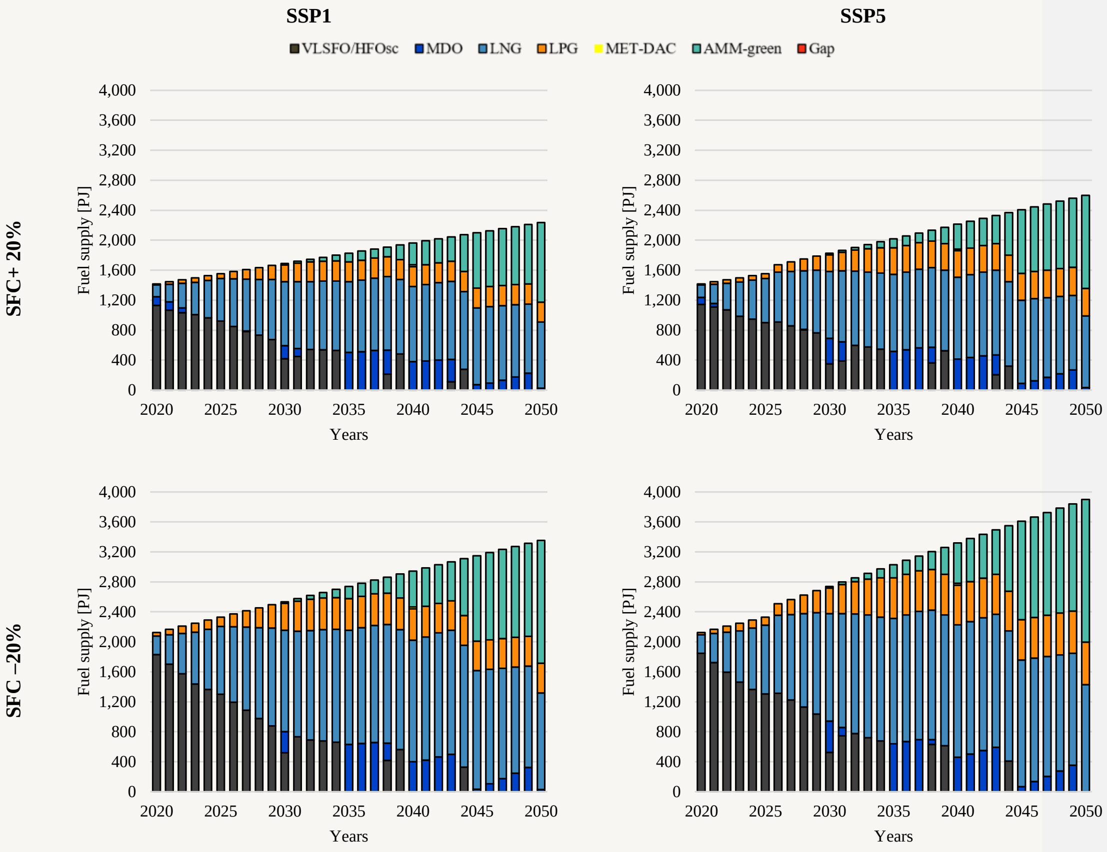

Figure 51: The impact of altering engine fuel efficiencies on the optimal fuel mix per SSP

Instead, between these model runs, large changes can be observed in the total fuel demand per year. If the SFC was increased by 20% from 2020 onwards, the total energy required for meeting shipping demand is far lower if there is better efficiency. Per illustration, the difference between -20% and +20% SFC in terms of cumulative energy demand in the observed time period is 28.3 EJ for SSP1 and 31.2 EJ for SSP5. To put this into perspective this is the equivalent of 7.4 - 8.1 times the EU renewable electricity production in 2021 [129].

This is energy that does not need to be supplied by RFNBOs and therefore frees up renewable electricity for other sectors which are also in the process of decarbonizing.

4.4.3 Fossil Fuel Price

Fossil fuels remain the most cost-effective fuel category throughout the observed time period. **Figure 20** and **Figure 21** show that costs per GJ for RFNBOs are significantly higher. Consequently, each model run outputs the minimum RFNBOs required for FEUM compliance. This section explores the impact of fossil fuel prices on the RFNBO demand as well as on the GHG emissions.

Figure 52 and **Figure 53** show the sensitivity of the model's outcome if the input variables for all fossil fuels are altered over a range of -50% to +400%. For simplicity's sake, the sensitivity analysis has only been carried out on the Esbjerg scenarios.

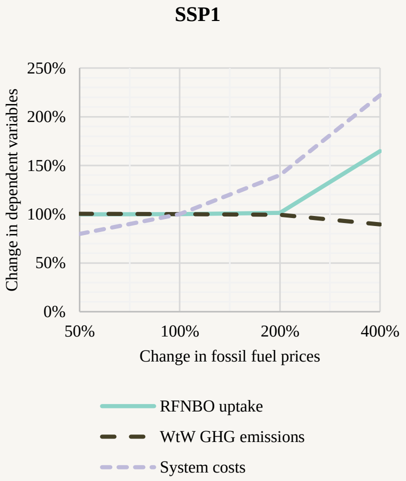

Figure 52: Change in RFNBO uptake and total emissions as a result of change in fossil fuel prices in **SSP1**

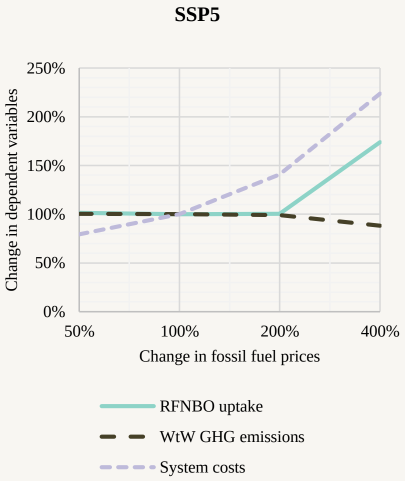

Figure 53: Change in RFNBO uptake and total emissions as a result of change in fossil fuel prices in **SSP5**

Considering the similarities between the two figures, there seems to be little difference in model sensitivity between SSP1 and SSP5. The model outputs remain unchanged between -50% and +200%, indicating that until this point fossil fuels are still more cost competitive compared to RFNBOs. Past +200% there is a sharp increase in RFNBO uptake, indicating that there is more RFNBO demand than is required for FEUM compliance.

If fossil fuels were to be four times as expensive from 2020 onwards, then total demand for RFNBOs would be up by 65% in the observed time period. The total percentage of energy supplied by RFNBOs in the observed time period would exceed 20%, a substantial amount considering the time required for scaling the RFNBO production capacity.

Unsurprisingly the total system costs increase significantly when increasing the price of fossil fuels. Increasing the fossil fuel price to 200%, increases total system costs to 140% and increasing to 400% would result in a system price increase of 220% for SSP1 and 224% for SSP5.

Most striking is the gradient for WtW GHG emissions. One would expect that a high price increase of fossil fuels would significantly impact the absolute emissions of the sector due to fuel switching. However, a 400% increase results in a mere 10% reduction in SSP1 and 12% in SSP5.

Figure 54 shows the fuel mix plotted over time for each model run performed in this part of the sensitivity analysis. If fossil fuel prices are increased to 200%, no significant changes appear in the optimal fuel mix. LPG gains some market share from LNG but overall patterns for NH_3 and VLSFO/HFO remain largely unchanged.

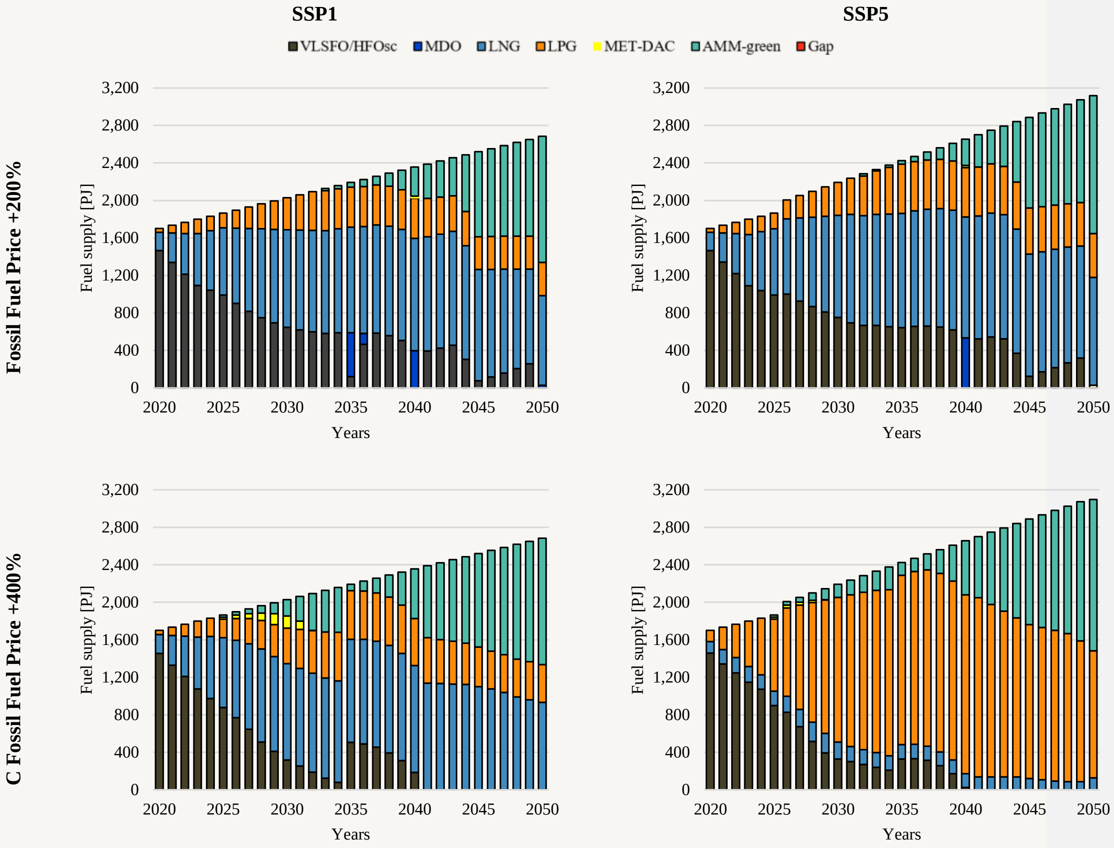

Figure 54: The impact of altering fossil fuel prices on the optimal fuel mix per SSP

In contrast, if increased to 400%, the outcome is remarkably different: In SSP1 there is a significant and early surge in RFNBO demand, even featuring some CH_3OH. Interestingly, this scenario experiences a large reduction in RFNBO demand in around 2035, after which it is poised to grow again. This reduction is experienced due to VLSFO/HFO being more than 4 times cheaper in 2035, and FEUM reduction targets still lenient.

In SSP5, VLSFO/HFO is quickly phased out and LNG does not gain in popularity much. Instead, LPG is the preferred fuel. Here too, a small decrease is experienced around 2035. Both scenarios experience more RFNBO uptake than is required under FEUM.

However, as previously mentioned this does not result in much absolute emission reduction. A more than doubling in fuel associated results in 10-12% absolute WtW GHG reduction. This indicates that legislation is the main driver for transition. A fuel tax could serve complementary but one this high is economically very unappealing. This is essentially the reason why FEUM has been adopted, as explained in **Section 2.1.1.**

5. CONCLUSION

This thesis aimed to answer the question: What are the techno-economic and emission implications of the FuelEU Maritime (**FEUM**) legislation? In doing so it evaluated various aspects, including the size and composition of the European Economic Area (**EEA**)-operating fleet, the optimal fuel from a cost minimization perspective while meeting FEUM compliance, associated emissions, and fuel-related costs to shipping companies, and the cost-effectiveness of abating Greenhouse Gas (**GHG**) emissions through maritime fuel transition. Additionally, the effect of various key underlying assumptions and input variables on outcomes was explored via sensitivity analysis.

Chapter 1 and **Section 7.2** highlight the novelty of assessing these implications across the entire EEA-operating fleet. This research presents insights into the potential effects of FEUM on the European maritime industry. These insights align with current literature and provide a comprehensive answer to the main research question:

The analysis performed underscores the instrumental role of legislation in driving the transition towards Renewable Fuels of Non-Biological Origin (**RFNBOs**). A transition which would not happen employing market instruments alone. The 2% sub-target in 2034 lays the groundwork for significant production growth in the late 2030's. NH_3 emerges as the dominant RFNBO due to its lower production costs compared to CH_3OH. Gaseous fuels such as LNG and LPG are set to replace liquid fuels despite higher fueling systems costs and will be in sustained demand well beyond 2050. Despite strict GHG intensity targets, the absolute emissions reductions by 2050 are modest and highly dependent on fleet growth rate. The high rate of fossil fuel allowance under FEUM in 2050 can be attributed to the reduced compliance requirements for extra-EEA voyages. The absence of blue fuel uptake highlights the legislation's favoring of RFNBOs. This analysis has found small variances of max 3% in GHG abatement costs across the considered RFNBO production locations, suggesting a limited impact on cost effectiveness of abating GHG emissions. The cost of abating GHG is roughly 10 times that of the global average for wind power. Initially, fuel associated costs premiums to shipping companies are relatively insignificant however, quickly escalate from 2040 onwards, projected to increase by 64-71% by 2050 depending on sector growth. A continuation of this post 2050 is very likely due to full decarbonization being out of reach, underscoring the financial implications as infrastructure costs were not included in this research. Reducing the total fuel associated costs by 8-10%, energy efficiency emerges as a promising avenue to in the effort to mitigate emissions and costs.

FEUM sets a positive trajectory towards a more sustainable European maritime industry, driving the transition towards electrofuels. However, it falls short of significant decarbonization by 2050 and is therefore not on par with Net Zero Emission (**NZE**) trajectories. Decarbonizing the maritime sector is imperative for achieving carbon-neutrality in global supply chains. While not perfect, FEUM sets a significant precedent and offers hope for the global shipping decarbonization effort, while highlighting the shared responsibility of this issue.

6. POLICY RECOMMENDATIONS

The FuelEU Maritime regulation is a positive step towards the decarbonization of the EEA maritime industry. However, the outcomes of this research have pointed out several shortcomings. This chapter therefore proposes both policy recommendations for FEUM directly as well as broader industry-focused strategies. All recommendations are based on the result of this research.

6.1 FUEM

Gradually increase the requirements for third party voyages: FEUM allows for staggering amounts of fossil fuels to be present in the fuel mix in 2050, largely due to the 50% must-comply requirement for third-party voyages described in **Section 2.1.2**. This differentiation exists so to not discourage shipping companies from operating in the EEA. However, as RFNBO prices start to drop, an increase in the required percentage can be a functional instrument to push fossil fuels out of the supply chain.

Higher/earlier RFNBO sub targets: In none of the scenarios ran, did the market forces alone meet the 1% sub target in 2031, which caused the 2% sub target to be mandated in 2034, as described in **Section 2.1.3.2**. RFNBOs are not required in large volumes until the late 2040’s. Knowing this, FEUM can steer on earlier or higher sub targets, boosting the RFNBO market.

Expand FEUM scope: The modelled EEA-operating fleet are ships that exceed 5,000 GT. However, 20% of maritime WtW emissions was be attributed to smaller vessels in 2021 [130]. For a holistic impact, these vessels need to be included.

Eliminate biofuel substitution option: Under FEUM, advanced biofuels can be used as a substitute to meet RFNBO sub targets without a multiplier, as described in **Section 2.1.3.2**. Eliminating this option provides RFNBO producers with a strong guarantee of demand for their fuels. Improving the business case and increasing competition by extension.

6.2 INDUSTRY-FOCUSED STRATEGIES

Encourage domestic RFNBO production: The costs differences observed between RFNBO production locations are marginal. This difference is expected to decrease further if the costs of doing business is considered. Promoting local RFNBO production ensures capital remains within the EEA, thus contributing to regional economic growth while reducing reliance on external production sources.

Implement stringent mandatory energy efficiency standards: Although GHG intensity of the fuel mix is reduced significantly due to FEUM, absolute emissions only marginally decrease, due to projected sector growth. Reducing the amount primary energy needed to meet shipping demand would help bring cost down and frees up renewable electricity capacity for other sectors.

Reevaluate LNG engine design standards: Most outcomes show a significant demand for LNG. However, recent research has pointed out that during operation, engine methane slip is twice the severity previously expected, resulting in far more GHG emissions than previously anticipated [130]. Switching fuels should reduce GHG emissions, not increase them. Until fixed, restrict permits for the acquisition of new LNG powered ships.

7. DISCUSSION

This chapter discusses the research results by addressing their limitations and theoretical implications. The chapter's aim is to provide a critical analysis of the research' findings and to align them with the overarching research aim and contributions outlined in the introduction.

7.1 LIMITATIONS

This chapter dives into a discussion of the research outcomes by addressing its limitations, theoretical implications, and FEUM policy recommendations. The chapter's aim is to provide a critical analysis of the research's findings and to align them with the overarching research aim and contributions outlined in the introduction. Many assumptions and decisions on which data to include or exclude had to be made in order to create a functional model. Additionally, several methodological decisions have had an effect on the results, which themselves have been interpreted in one way but which could be explained another. This and more is outlined and discussed below:

7.1.1 Assumptions

- **Electrolyser technology:** All green hydrogen was assumed to be produced using SOEC technology. This opted for in the research design phase so as to not get too many different scenarios. Other electrolyser technologies outlined in **Section 2.4.1.1** are currently more mature and therefore more cost-effective until projected to be overtaken in 2030. Including other types of electrolysers could result in earlier uptake of RFNBOs. However, significant changes seem unlikely due to the enormous cost gap between RFNBOs and fossil fuels combined with mild GHG intensity reduction targets before 2030.

- **Fuel price linearity and lack of price elasticity consideration;** Fuel costs were assessed at ten-year intervals with the assumption of linear relations between intervals. In reality, market dynamics are characterized by fluctuations and dynamic pricing. Furthermore, no consideration was given to price elasticity of fuels. The oversimplification of these economic dynamics could impact research results and give avenues for further research.

- **Engine efficiency;** This research assumes no efficiency gain for vessels exceeding 5,000 GT since marine engines are a mature technology, having reached the limits of their economic optimum. However, this economic optimum may shift as the sector shifts fuel consumption. Additionally, assumptions were made that in DF engines, the engine enjoys the same efficiency for both fuels. The expected ammonia engine is assumed to have the same efficiency as well, although this cannot yet be confirmed.

- **Grid decarbonization by 2040;** A significant cost component of RFNBO is electricity and by extension the electricity supply strategy employed. This research assumes a fully decarbonized grid by 2040, which allows producers to opt for the most cost-effective strategy, which is the hybrid strategy. This lowers the price of RFNBOs significantly as the plant can now run continuously with minimal forms of energy storage. If grids are not decarbonized by 2040, then prices of RFNBOs past this point are not reliable. This would most likely influence the GHG abatement costs but not the optimal fuel mix, as no alternatives exist which can achieve the stringent reduction targets post 2040.

- **Engine technology pricing;** While fuel prices are dynamic and expected to go down over time, prices for fuel systems are assumed to be static throughout the observed time period. Improvements in manufacturing prices could have a big impact on which engine technology is opted for by shipping companies. This assumption was made out of lack of reliable projections for engine technology costs.

Commented [EK12]: In Rubric komt conclusie voor de discussie. Dit klopt in mijn ervaring ook. Je begint met je conclusie na je resultaten. Daarna kan je in je discussie va de conclusie beperkingen en limitaties van je onderzoek bespreken en suggesties geven aan mede-onderzoekers vo vervolgend onderzoek.

Commented [EK13]: In je discussie is het belangrijk on helder te schetsen wat je contributie is aan de samenleving/wetenschap/bestaande theorie/bestaande methodes. Dit heb ik nog onvoldoende teruggelezen.
Wat is kritiek die het onderzoek van de Denen heeft gekregen? Kan je dat op een bepaalde manier gebruiken a toets op je eigen discussie punten?
In Rubric staat:
Research methods and results are reflected upon.
Substantiation for contribution to theory, practice or socie
Deze zie ik nergens terug in de discussie (omdat ideeën m weinig context worden aangedragen). Dit zou je kunnen oplossen met een langere eerste paragraaf die introducere werkt. En ook de onderbouwing van het argument voor waarom de limitatie/policy recommendation/suggesties vo nader onderzoek is gegeven vind ik in stukken nog dun. Waren je resultaten op stukken op een andere wijze te interpreteren? Waarom zou die interpretatie niet de juiste zijn? Dat lees ik nog niet terug in de discussie (en wel belangrijk volgens Rubric).
Volgens mij pas je in delen wel een structuur toe 'eerst: id daarna waarom'. Als dit een vaste structuur is die je gebru in het naar voren brengen van je ideeën, dan zou ik dit ook expliciet benoemen in een introductie.
Je identificeert interessante research topics, maar kan je di nog meer in sweet spot van het doel van je onderzoek toespitsen?
Probeer weer in (eigen bewoordingen) de tekst van rubric voor bepaalde beoordeling op strategische wijze te gebrui om te signaleren dat je onderdelen die nodig zijn voor een bepaalde beoordeling "aftikt". This paragraph delves into rival interpretations ... Etc.". Of blabla zoals: "the discussi of limitations includes a substantion for why this cut-off point was made".

Commented [KE14]: Na het gelezen te hebben, vraag ik me ook af: in hoeverre zijn de type data waar je model in gelimiteerd is, te vinden/beschikbaar? Of complex om zel berekenen? Dat zou voor mij als lezer een duidelijkere onderbouwing zijn waarom je het niet hebt meegenomen.

7.1.2 Data limitations

- **Exceptional circumstances base year;** The modelling of the EEA-operating fleet was performed using entries from the MRV database in the year 2020, which was marked by the outbreak of the COVID-19 pandemic. Across categories, this caused substantial shifts in shipping demand. Orders for consumer goods surged while demand for ferry services and cruise liners decreased during lockdown periods. The year 2020 was used since it is the base year employed by FEUM legislation. While GHG intensity factors are unaffected by this due to their relative nature, the distribution of shipping demand is most likely skewed due to the abnormal distribution in this year, meaning this error protrudes due to the extrapolation of the IMO projections.

- **Fuel price linearity and lack of price elasticity consideration;** Fuel costs were assessed at ten-year intervals with the assumption of linear relations between intervals. In reality, market dynamics are characterized by fluctuations and dynamic pricing. Furthermore, no consideration was given to price elasticity of fuels. The oversimplification of these economic dynamics could impact research results.

- **Fuel production costs data;** Was adopted from the “MarE-fuel: LCOE and optimal electricity supply strategies for P2X plants” [43]. Relying on a single source poses a bias thread, however it was deemed necessary and even offered an advantage. Unfortunately, data on alternative fuel costs projections is not readily available, and sources vary greatly when they are. Projecting the costs for alternative fuels over the observed time proved to be too complex and time-consuming given the available timespan. The single source approach allowed for efficient data management.

- **Equal techno-economic assumptions for fuel plants across locations;** The difference between RFNBO prices if produced in Esbjerg or Dakhla are based only by differences in LCOE. This oversimplification neglects the multifaceted factors which influence the cost of doing business in various geographical locations. Setup and operational costs will most likely prove to be much higher for Dakhla than for Esbjerg. Expenses such as the cost of importing labor and the higher cost of capital associated with regions with political/economic instability due to risk, were not considered in assessing RFNBO prices.

Commented [KE15]: "in respectively Esbjerg? And Dakhla"

7.1.3 Choices for including/excluding data

- **Exclusion of infrastructure costs;** The cost of infrastructure was not considered. The decision for this stems from the inherent complexity of obtaining the required techno-economic data as well as the shared responsibility between government, and suppliers associated with fueling infrastructure. This limitation likely has a large impact on the economic results of this study as these costs are in part passed on to fuel buyers.

Commented [KE16]: Ik vind dit niet voldoende uitleg geven waarom je het niet hebt opgenomen? Je bedoelt te zeggen dat het heel complex is om infrastructure costs te berekenen omdat het inherent aan infrastructuurproject is deze complex zijn en door meerdere stakeholders uitgevoerd/gefinancieerd worden? Ik vind het ook dun onderbouwd waar de impact van deze variable terug te zie zouden zijn in de results. Costs? Wat voor costs? En de consumer =?? Is niet de juiste term om hier te hanteren.

- **FEUM instrument not considered;** Several FEUM instruments could not be effectively modelled or added. These include the shoreside electricity mandate for container ships and cruise liners, as well as the pooling system and the penalty system. The first is expected to have marginal effect, the latter two are company specific choices, which is game theory and requires a different modelling approach.

- **Excluded retrofitting;** The model does not allow for retrofitting of relatively new vessels. This is an oversimplification as most vessels nowadays are designed with retrofitting in mind. This cost-effective way of converting ships could prove very important to the maritime fuel transition as it will have an effect on the fuel associated costs due to fueling system parts reusability.

- **No handling risk considered;** Handling risk is a major concern for shipping companies. A fuel spill could harm both crew and marine life. Every risk incurs a cost, which could influence the choice for future fuels. This study did not evaluate the handling risks associated with fuels.

7.1.4 Methodology

- **Macro-micro discrepancy in decision-making dynamics;** The objective of the study's modelling exercise was to yield easily interpretable results on EEA fuel mix trends at a system level. Because the modeled system exhibits a high degree of complexity and has a runtime of 30 years, a macroscale approach was chosen to enhance modelling efficiency. However, this approach rests on the assumption that decisions are made at the system level, whilst in reality individual entities make choices driven by commercial gain. A hybrid modeling approach which combines elements from both macroscale and microscale approaches could allow for a more nuanced understanding of the system.

- **Modelling exercise bias;** The model possesses a one-sided perspective by assuming that shipping companies have unimpeded access to all fuels (and can switch between them) once the production capacity of the respective suffices. This perspective neglects the dynamics fuel suppliers face in the market. The choice between fuels is not only influenced by their price and production capacity but is also impacted by long term delivery contracts, storage availability and plant lifetimes.

- **Exogenous modelling of shipping demand projection;** As discussed in **Section 3.4.4**, the shipping demand was projected based on extrapolation of IMO projections in the fourth GHG study. In that same report the organization writes that a suboptimal methodology was employed due to lack of available data. Instead, the suggestion is made to supplement the method with a gravity-based model. Due to the extrapolation, errors in their assessment of future shipping demand emulate in this work.

- **Growth rate;** In addition to the previous point on exogenous modelling, this research has adopted the increase in shipping demand projected by the IMO on the basis of extrapolation. However, the scopes of the IMO and this research are global and regional. This approach therefore assumes that trends in the global shipping sector are directly applicable to the European shipping sector, which is an oversimplification as geographical markets experience different levels of growth. Most likely, the EEA experiences slower levels of expansion compared to the rest of the world due to its relative maturity. This adjustment in growth rate was not taken into account.

- **Excluded from FEUM;** Because of modelling purposes, the share of the EEA-operating fleet which is excluded from FEUM is not excluded from the model. Instead, the entire fleet needs to adhere to the one GHG cap based on the share of intra-EEA and extra-EEA-operating fleet. This could impact the fuel of choice for this unregulated share.

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minder hard gaat groeien dan global (want opkomende economien) Daarom kan het teveel zijn.

7.2 RESEARCH CONTRIBUTION

This research aimed to assess the techno-economic-environmental implications of the newly adopted FuelEU Maritime legislation. By collaborating with researchers from the DTU who investigated various decarbonization pathways for the global maritime industry, an effective and timely study could be conducted and submitted six months after the adoption of FEUM. In terms of adding to the scientific debate, the literature review employed in this thesis reveals that this is the first modelling of its kind with the scope of FEUM across the entirety of the EEA-operating fleet.

T&E has published on the effects of FEUM on the container shipping market. However, these results cannot simply be extrapolated to the rest of the fleet due to significant differences in category efficiency and demand. Similarly, the MarE-fuel research group have modelled across all categories but used a global scope and theoretical reduction pathways. This research bridges these works, in answering its research question.

Operating at the frontier of energy science, this study closely aligns with it by assessing the fuel transition in one of the most notorious hard-to-abate sectors due to legislation that was adopted less than six months ago. Positioned at the intersection of energy, economics and governance, the findings offer valuable insights for both shipping companies, fuel suppliers and policy makers.

Shipping companies and fuel suppliers can use these insights to hedge risks and alter operation models. They now know the timeline at which change is mandated and more importantly to what extent. Policy makers can use the outcomes design future legislation iterations. The hypothesis of the author is that legislation will likely become more stringent, provided technological advancement allow it.

Extensive use of the SEAMAPS model and constantly questioning it facets, contributed to validating this model. Additionally, several suggestions for modelling improvement were made in close collaboration with the authors.

7.3 RESEARCH IMPLICATIONS

This research gauged FEUM's effectiveness in reaching its goal: Reducing the EEA-operating fleet's impact on atmospheric GHG emissions. The results of this study indicate that while this legislation is a step in the right direction, in terms of absolute annual GHG emissions limited reduction will be achieved, while costs to shipping companies increase greatly. This and other outcomes give several avenues for further research:

- **Conduct a risk reward analysis: Investigate the cost and efficiency of fuel handleability for all alternative fuels;** Handleability is a term which is difficult to quantify but is of the utmost importance to shipping operations. Companies therefore tend to operate within extremely strict safety margins. Assessing the safety limits and cost associated with handling all alternative fuels could help reduce skepticism in the industry when it comes to handleability of alternative fuels.

- **Investigate the macro-economic implications of increased shipping rates;** As mentioned in **Chapter 0**, shipping represents 90% of global trade. If it gets more expensive it will have a ripple effect on the rest of the economy. An example of this is the perceived gas shortages short after the Russian invasion of Ukraine. The increased price of natural gas was a catalyst for rampant inflation across the European continent. Assessing the economic implications is necessary so that adequate measures can be designed.

- **Investigate the multiplier effect;** An increased shipping rate will affect the price of consumer products. Literature review has pointed out current research investigates only the trip from producer to consumer. However, this paints an incomplete image since in a globalized economy components that make up consumer products often require shipping from production locations to the assembly plant. Often assembly is done in multiple phases at different locations. This multiplier effect could potentially have a big impact on the way producers structure their production facilities. Research would be needed to assess the effect of this multiplier.

- **Investigate the impact of FEUM on the competitiveness of EEA-produced goods;** EEA producers will most likely see exports to non-EEA countries drop, due to higher shipping rates which are passed down in the value chain, leading to higher prices to the end-consumer. The same effect could be observed in import from non-EEA producers and needs to be analyzed per sector based on elasticity. Additionally, FEUM could negatively impact the local EEA market. The 50% must-comply mandate for third-party voyages versus 100% must-comply for EEA voyages, could give non-EEA producers a strategic cost-competitive advantage over EEA producers in their own market.

- **Extend the scope of this research;** Considering more synthetic fuels like e-diesel, e-LNG, e-DME as well as other solutions such as assisted wind power and onboard CCS could provide useful outcomes beyond the scope of this research study. In addition, researchers could consider including fuel cells as onboard energy transformers. Other forms of water electrolysis could be considered such as AE and PEME. Finally, more production locations could be taken into account.

- **Study the effect of herd behavior in shipping companies anticipating FEUM;** This effect is crystallizing already. Shipping companies are imitating the actions of the first mover, which is Maersk. Maersk has a clear inclination towards CH_3OH despite its significantly higher costs due to handleability of the CH_3OH. Already, other companies imitate their move, which could jumpstart the CH_3OH economy and keep NH_3 from gaining momentum. Impact examination may unveil decision making patterns, providing valuable insights for legislation.

8. ACKNOWLEDGEMENTS

I express my deep gratitude to all who played a role in the creation of this work; it would not have been what it is without your contributions.

Firstly, Prof. Dr. Gert Jan Kramer deserves special acknowledgment for not only guiding the trajectory of this research, but also consistently challenging it. This path of most resistance refined the work in the process. A sincere thank you also extends to his friend and former colleague Dr. Hans Potters, whose meticulous red pen has certainly left its mark on this work.

To Elaine Kreiken and Jan Karel van den Biesen from Accenture. I could not have asked for better supervisors or for a better work environment. Your supplementary and friendly guidance was truly a blessing, as it instilled the confidence and freedom to delve deep into this intricate topic. In the beginning we were novices to the maritime sector, now we are not (so much) anymore.

Nicolas Campion and Sebastian Franz from DTU, your collaboration was truly appreciated, this work would have looked utterly different without access to the SEAMAPS model. Additionally, taking time from your schedules to address queries about your script greatly enriched this project. A special mention to UU's Claudio Pierard whose knowledge on the Julia programming language proved very insightful.

Finally, heartfelt thanks go out to the members in my family who have aided by lending strategic insights, proofreading and offering moral support. I consider myself profoundly lucky to have such an extraordinary family.

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10. ANNEXES

A

The detailed versions of the equations used by independent verifiers to calculate TtW and WtT emissions:

TtW
[CO₂/MJ]

$$\frac{\sum_i^{n_{\text{fuel}}} M_i \times CO_{2\text{eqWT},i} \times LCV_i + \sum_k E_k \times CO_{2\text{eq electricity},k}}{\sum_i^{n_{\text{fuel}}} M_i \times LCV_i + \sum_k E_k} \qquad [25]$$

$$+$$

WtT
[CO₂/MJ]

$$\frac{\sum_i^{n_{\text{fuel}}} \sum_j^{n_{\text{engine}}} M_{i,j} \times \left(1 - \frac{1}{100} C_{\text{engine slip},j}\right) \times CO_{2\text{eqTW},j} + \left(\frac{1}{100} C_{\text{engine slip},j}\right) \times CO_{2\text{eqTW,slippage},j}}{\sum_i^{n_{\text{fuel}}} M_i \times LCV_i + \sum_k E_k} \qquad [26]$$

Here ***i*** corresponds to the fuels delivered to a ship per reference period; ***j*** to the fuel combustion units on board; ***k***, to the electrical connection points; ***c*** to the number of electrical charging points; ***m*** to the number of energy consumers; ***M*** to the mass of a specific fuel combusted in [grams of fuel]; ***E*** to the electricity delivered to the ship [MJ]; ***CO₂eq_WtT,ᵢ*** and ***CO₂eq_electricityₖ*** are the Well-to-Tank GHG emission factors for fuel (*i*) and electricity (*k*), in [gCO2eq/MJ]; ***CO₂eq_TtW,ᵢ*** is the Tank-to-Wake emission for fuel (*i*); ***LCVᵢ*** is the Lower Calorific Value of the fuel combusted in [MJ/gFuel] and ***C_engine slip_j*** is the engine fuel slippage coefficient which denotes the percentage of fuel that escapes the engine.

B

A

$$min_{x,q,z,d}{}^{EF} \sum_{s,y} SI_s \cdot NewBuildShips_{s,y} + SOM_s \cdot ShipStocks_{s,y} + SI_s \cdot Decom_{val} \cdot Decommissions_{s,y}^{EF}$$

B

$$+ \sum_{s,f,y} FuelUsed_{f,s,y} \cdot FC_{f,y}$$

In the formula, $\mathbf{min}_{\mathbf{x,q,z,d}}^{\mathbf{EF}}$ represents the goal of minimizing the total costs for the maritime industry, considering a variety of factors: $\mathbf{SI_s}$ is the CAPEX required for acquiring a new vessel of type ***s***. $\boldsymbol{NewBuildShips_{s,y}}$indicates the number of new ships of type ***s*** purchased in year ***y***. $\boldsymbol{SOM_s}$ corresponds to the O&M for each vessel type ***s***. $\boldsymbol{ShipStocks_{s,y}}$ is the total number of operational ships of type ***s*** each year ***y***. The $\mathbf{Decom_{val}}$ factor reflects the premature decommissioning penalty and is set at $\frac{1}{2}$ CAPEX. $\boldsymbol{Decommissions_{s,y}^{EF}}$ represents the number of ships to be decommissioned by the model. $\boldsymbol{FC_{f,y}}$ represent the fuel cost fuel type ***f*** and year ***y***. $\boldsymbol{FuelUsed_{f,s,y}}$ stands for the fuel consumption by ship type ***s*** and year ***y***. Together, these components form a detailed framework for optimizing costs in maritime operations, balancing fleet management and fuel efficiency considerations.

Commented [KE19]: deze afkorting eerder introdcueren onder Fleet-related costs -> operational and maintenance (O&M) costs

Commented [Jv20]: Zijn er ook kosten als een schip aa het eind van de levensduur raakt en ontmanteld moet worden?

Commented [MF21R20]: Die zijn er, maar ook in de huidige situatie. Die kosten zijn dus niet toe te schrijven a brandstoftransitie

C

The energy content, GHG intensity and fugitive emission percentages of all fuels considered in this research as standardized values as per Annex II of FEUM [34].

		LCV	CO_{2eq} WtT	C_f CO_2	C_f CH_4	C_f N_2O	C_{slip}
		MJ/kg	gCO2eq/MJ	gCO2/gfuel	gCH4/gfuel	gN2O/gfuel	%
Fossil	HFO	40.5	13.5	3.114	0.00005	0.00018	0
	VLSFO	41	13.2	3.206	0.00005	0.00018	0
	MDO	42.7	14.4	3.206	0.00005	0.00018	0
	MGO	42.7	14.4	3.206	0.00005	0.00018	0
	LNG	49.1	18.5	2.775	0.00000	0.00011	3.1
	LPG	46	7.8	3.03	t.b.a	t.b.a	0
Biofuels	LBG	50	27.77	2.775	0.00005	0.00018	3.1
	Ref-PO	16.3	5.93	3.155	0.00005	0.00018	0
RFNBOs	E-methanol	19.9	0.655	1.375	0.00005	0.00018	0
	E-ammonia	18.6	0	0	-	0	t.b.a

D

To model current fleet size, emissions, fuel consumption and shipping demand several assumptions had to be made. These assumptions and justifications are listed below:

Assumption	**Clarification/justification**
Voyage share	Between intra and extra EU voyages was assumed to remain static throughout the model. Changing the share throughout would unnecessarily complicate the model and could diminish the clarity of results.
Fuel mix	Was assumed to be homogenous across the fleet, while in reality the fuel mix varies per ship type. This generalization was necessary due to disparity in available data.
Engine efficiency	Was assumed to remain static throughout the fleet. Due to the economic maturity of marine engine technology.
EEDI	was used to calculate transport work of average ships. EEDI sets the minimum efficiency requirement for ships to be allowed to sail. Assuming that most ships comply, the transport work (gt·nm) delivered will most likely be higher than modelled. A more accurate metric would be the Energy Efficiency Operational Index (**EEOI**), which reflects actual energy efficiency rather than minimal efficiency. However, EEOI data in the MVR database was incomplete and contained too many outliers to be considered reliable.
Average vessel lifetime	Was assumed the scrapping age in this model.
Linear decline	Was assumed between age buckets.