Reducing Emissions from Short-Sea Ships
Cost Effectiveness of Available Options

Masters Dissertation

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Reducing Emissions from Short-Sea Ships

Cost Effectiveness of Available Options

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Preface

The developments in emission reduction technologies in the maritime sector accelerated in recent years. In a broader sense, the acceleration of innovation in technology in the world is having a increasing impact on the way companies make money and people's way of living. Perhaps this is true for every generation, but I can't stop wonder about how we as humans will deal with the problems of this time. The transition of the maritime sector to net zero emissions brings with it many uncertainties and it is increasingly important to have a clear picture of the interaction between technology, its financial feasibility and stakeholders in order to make robust and informed choices.

This report aims to provide such an overview of the challenges in choosing the right strategy for reducing carbon emissions for ships. And incorporates these in a tool that supports shipowners and financiers in their investment choices, providing parts of the solution to achieve the carbon emission reduction goals by the maritime sector. And I feel grateful to contribute to the transition to low-carbon shipping. This research has been made possible with the help of a large number of people, and would not have been what it is today without their help. I would like thank the ship finance company NESEC for sharing their financial expertise. Special thanks to Pieter van der Burg, Joost Bout and Erik Wesseling of the NESEC team for providing valuable insights into ship financing. Furthermore, I would like to thank Jeroen Pruyn from Delft University of Technology for his extensive feedback on my writings and the academic methods used.

I can't see what's beyond the horizon, but I'm eager to set course for a sustainable future.

Jacco Nollen
Rotterdam, 2023

Summary

The shipping industry is a significant source of (greenhouse gas) emissions, due to the combustion of carbon based fuels. Carbon Dioxide (CO_2) emissions are the most dominant source of shipping's climate impact, and it constitutes of around 2.89% of global CO_2 emissions. The emissions of ships have impact on ecosystems, climate change and human health. To reduce the impact of ship exhaust emission, governments and international organizations place direct requirements on ships on both a regional and global level. Global regulations are introduced by the International Maritime Organisation (IMO); the Energy Efficient Design Index (EEDI) for new built ships in 2013, Energy Efficiency Existing Ship Index (EEXI) for existing ships in 2023 and the Carbon Intensity Indicator (CII) in 2023. The EEDI and EEXI are related to the technical efficiency of a ship and the CII to the operational efficiency of vessels. Furthermore, regional regulations are introduced by the European Union (EU) by the inclusion of shipping in the EU Emission Trading System (EU ETS) from 2024 forward. New-built and existing ships will have to comply to these regulations to stay in business. Moreover, companies who finance ships are increasingly taking the emission profile of a ship into account when providing capital to shipowners. To reduce credit risk and the risk of stranded assets, financing parties require ships to comply to current emission regulations, and require ships to be ready for more stringent regulations in the future.

Several strategies and measures provide solutions to reduce carbon emissions. These can be divided into low-emission fuel strategies, operational strategies and adding technical emission reduction technologies. All of these have effects on the operation, design and profitability of vessels. This research compares emission mitigation measures and low-emission fuel strategies for short-sea ships, within the constraints of regulatory compliance. To achieve this, the Comparison Tool is introduced, which determines the financial viability of measures and the effect of measures on regulations based on a set of technical and operational ship inputs. This supports shipowners and financiers in making sound investment decisions. Additionally, the results from the Comparison provide insight to into the effect of regulatory incentives to regulators.

The Comparison Tool calculates CII, EEXI ratings and cost of EU emission allowances for an input of a vessels technical and operational characteristics. Additionally, the model specifies the net present value of an investment in a single measure, and the effect this has on the vessel's CII, and EEXI rating. Feasibility of measures is determined based on technical requirements (e.g. weight, space, installed power, etc.) and Technology Readiness Level (TRL) of individual measures. The effect of measures on CII, EEXI values are based on their impacts on the engine power, carbon content of fuel, specific fuel consumption, vessel's transport capacity, vessel's speed, fuel consumption and distance sailed per year. The financial viability of an investment in a measures is determined based on a cash-flow analysis. In which a reduction in cost for EU emission allowances and fuel, and increased transport capabilities result in a positive cash-flow, and the capital cost, OPEX, lost opportunity cost and increased fuel cost present a negative cash-flow.

a case study is performed for five representative short-sea vessels that together represent 75% of the short-sea fleet till 15000 DWT. The vessels are analysed for their compliance to CII and EEXI regulations. Additionally, the financial viability of emission reducing measures are compared for these vessels and their effects on CII and EEXI are determined. To obtain valid results, the data inputs into the model must accurately reflect the technical and operational characteristics of each reference vessel. The technical ship inputs are obtained from technical data sheets provided by shipbuilding companies. Operational data for the reference vessels is obtained from the THETIS database, which provides actual (verified) data of CO_2 emissions, fuel consumption, and distance sailed of vessels sailing in the European Area. Furthermore, sensitivity of the cost of measures is determined by analysing results for a low, base and high-case price scenarios for fuel prices, EU emission allowance prices and time charter rates. In which a low case represent a worst case scenario in which price negatively affect cost effectiveness of measures. The base case is the expected trajectory of prices. And the high case is a scenario in which price are more favorable for costs of measures.

The results of this research provide a clear overview of regulatory compliance of the short-sea fleet. In general, short-sea vessel amply comply with EEXI regulations. The compliance to CII regulations depends on vessel type and size.

The results from the Comparison Tool show that only 7 measures provide significant carbon reduction that offer solutions to comply with CII regulations (when a vessel does not comply). These measures consist of low-emission fuel strategies; LNG, LPG, hydrogen and fully electric, and technical measures; capacity increase, carbon capture and slow-steaming (engine-derating). The low-emission fuel strategies hydrogen and fully electric do not offer financially viable solutions, with highly negative net present values. LNG and LPG do offer financially viable solutions to comply to CII regulation and have a positive net present values for the expected price scenario. Additionally, slow-steaming (engine power limitation) and carbon capture and storage offer financially viable solutions to comply with CII regulations. Moreover, increase in transport capacity offers a solution to reduce CII and EEXI ratings. The installation of a single technical measures that improves propeller efficiency, hydrodynamic efficiency, or a fixed wing or sail has insufficient carbon reduction potential to have significant effects on CII, but offers financially viable solutions with positive NPVs for smaller vessels. A combination of these measures might have an higher carbon reduction potential, although the effect of an individual measures might be reduced.

Furthermore, the effect of the inclusion of EU ETS on costs for small vessel show that inclusion results in higher incentives for shipowners to install measures that reduce significant amounts of carbon emission.

Further development of the Comparison Tool can expand the scope to other vessel sizes and types. Supporting shipowners and financiers in their investment decisions, and creating more impact to achieve the carbon reduction targets of the maritime sector.

Contents

Acronyms

Symbols

Attained EEXI	Attained EEXI original vessel	[tCO2/DWT·nm]
New Attained EEXI	Attained EEXI after implementation of measure	[tCO2/DWT·nm]
$\Delta EEXI$	Change of EEXI rating	[%]
Attained CII	Attained CII original vessel	[tCO2/DWT·nm]
New Attained CII	Attained CII after implementation of measure	[tCO2/DWT·nm]
ΔCII	Change of CII rating	[%]
P_{ME}	Original main engine power at 75%MCR	[kW]
Cf_{ME}	Carbon factor of fuel in main engine	[tCO2/t]
SFC_{ME}	Specific fuel consumption main engine at 75% MCR	[g/kWh]
P_{AE}	Auxiliary engine power at 50% MCR	[kW]
Cf_{AE}	Carbon factor of fuel in auxiliary engine	[tCO2/t]
SFC_{AE}	Specific fuel consumption auxiliary engine at 50% MCR	[g/kWh]
C	Transport capacity	[DWT]
S	Ship speed at 75% MCR main engine	[kt]
FC_{ME}	Fuel consumption main engine per annum	[t/yr.]
FC_{AE}	Fuel consumption auxiliary engine per annum	[t/yr.]
D	Total distance sailed per annum	[nm]
NPV_m	Nett present value of investment in measure	[EUR]
CF_{m}	Annual cash flow of measure	[EUR/yr]
r	Discount rate	[-]
LT	Lifetime of asset	[yr]
WACC	Weighted Average Cost of Capital	[-]
SC_i	Source of capital	[-]
AR_m	Annual repayment of investment in measure	[EUR/yr]
I	Initial asset value	[EUR]
AV_m	Asset value in specific year i	[EUR]
C_{im}	Annual financing cost in a specific year i	[EUR]
R_{WACC}	Annual weighted average cost of capital	[-]
Δm_{CO2m}	Change in mass CO2 emitted due to measure	[tCO2]
m_{TAFC}	Total (mass) annual fuel consumption main engine	[t]
$C_{FR\%m}$	Average annual fuel reduction percentage of measure	[-]
$\Delta C_{\mathrm{fuel}m}$	Change in fuel cost due to measure	[EUR]
P_{fuel}	Fuel price	[EUR/t]
ΔC_{EUETSm}	Change in EU ETS cost	[EUR]
$P_{EU\ ETS}$	EU ETS Allowance price	[EUR/tCO2]
V_{EU}	Percentage voyages between EU ports	[%]
$V_{EU,nonEU}$	Percentage voyages between EU and non EU ports	[%]
$OPEX_m$	Annual Operational Expenses of individual measure	[EUR]
CR_m	Percentage carbon emissions captured	[-]
ΔP_{ME}	Power reduction main engine	[kW]
$P_{\mathrm{fuel\ ULSFO}}$	Fuel price ULSFO	[EUR/t]
$P_{\mathrm{fuel\ HFO}}$	Fuel price HFO	[EUR/t]
U_{ULSFO}	Energy density ULSFO	[GJ/t]
U_{HFO}	Energy density HFO	[GJ/t]
S_{wa}	Hull wetted area	[m2]
L_{wl}	Waterline length	[m]
C_m	Mid-ship block coefficient	[-]

C_{wp}	Water-plane area coefficient	[-]
C_b	Block coefficient	[-]
B	Beam of the vessel	[m]
T	Draft of the vessel	[m]
ΔD_{TCE}	Change of number of days with TCE income	[days]
D_{s0}	Days at sea before speed reduction	[days]
D_{p0}	Days in port before speed reduction	[days]
$SR_{\%}$	Percentage speed reduction	[-]
ΔIC_m	Change in income of vessel due to measure	[EUR]
TCE_{rate}	Time charter equivalent	[EUR/day]
$\Delta\,\mathrm{Cap}_{dwt}$	Percentage dwt capacity increase	[-]
C_c	Correction factor TCE income	[-]
d_1	Annual distance sailed after speed reduction	[nm]
D_{p1}	Days in port after speed reduction	[days]
D_{s1}	Days sailing after speed reduction	[days]
P_{MCR1}	Max MCR main engine after engine power limitation	[kW]
P_{MCR0}	Max MCR main engine before engine power limitation	[kW]
SFC_{ME1}	SFC at 83% MCR main engine, adjusted for ME power limitation	[g/kWh]
m_{TAFC_1}	Annual fuel consumption main engine of alternative fuel	[t]
$PF_{\%}$	Percentage diesel pilot fuel required for alternative fuel	[-]
E_f	Energy in fuel	[kWh]
η_e	Effective efficiency engine for specific fuel	[-]
V_t	Volume of alternative fuel tank	[m3]
D	Annual distance sailed	[nm]
d_{voy}	Maximal voyage distance to cover 90% of routes	[nm]
U_{vf}	Volumetric energy density of original fuel	[GJ/m3]
m_t	Mass of alternative fuel	[t]
C_{f0}	Carbon factor of original fuel	[tCO2/t]
C_{f1}	Carbon factor of alternative fuel	[tCO2/t]
$P_{\mathrm{fuel\ 1}}$	Fuel price of alternative fuel	[EUR/t]
P_{fuel0}	Fuel price of original fuel	[EUR/t]

1. Introduction

1.1. Problem Background

The shipping industry is a significant source of Greenhouse Gas (GHG) emissions, due to the combustion of carbon based fuels. The emissions of ships have impact on ecosystems [Eyring et al., 2007], climate change [Eyring et al., 2010] and human health [Winebrake et al., 2009]. Carbon Dioxide (CO2) emissions are the most dominant source of shipping's climate impact, when calculated on a global warming potential (GWP-100) basis [IMO, 2020]. And it accounts for 98% of total international GHG emissions in CO_2 equivalent [IMO, 2020]. Moreover, shipping CO_2 emissions constituted of around 2.89% of global CO_2 emissions in 2018 [IMO, 2020]. At the EU level, the maritime sector is an even higher CO_2 emitter, representing 3 to 4% of the EU's total CO_2 emissions in 2019 [EC, 2021]. Due to a rising demand for sea-born transport services and reducing emissions in other sectors the global CO_2 contribution of the shipping sector is likely to increase to 17% by 2050 under a business as usual scenario [Cames, 2015].

Furthermore, human exposure to pollutants from ships has been associated with a number of health effects [WHO, 2006]. Key air pollutants from shipping exhaust emissions include Particulate Matter (PM), Sulphur Oxides (SOx) and Nitrogen Oxides (NOx), which impacts are at a local level. Port and coastal cities have an additional pollution burden from shipping emissions [Di Natale et al., 2022]. In European coastal area's, shipping emissions have significant contribution to PM pollution, attributing to 1-14% of local PM emissions [Viana et al., 2014]. NO_x levels in European coastal area's contributed by the shipping sector range from 7-24%, with the highest values recorded in the Netherlands and Denmark [Viana et al., 2014]. On average across Europe, shipping emissions contributed to 8% of populations exposure to PM, 16.5% of population exposure to NO_x and 11% of population exposure to SO_x [Viana et al., 2014].

Of the total pollutants from ships in Europe, short-sea shipping (mainly operating in coastal areas between European ports) is a major source of emissions [Eurostat, 2022]. This is reflected in the tonnage transported in the European area, with short-sea shipping accounting for about 60% of the maritime transport of goods (in tonnes) to and from European ports [Eurostat, 2022]. The pollution impact of short-sea activities are even more concentrated in the Netherlands and Italy, which counties represent 14.2% and 14.4% of total tonnage of short-sea shipping in Europe in 2020. Since short-sea shipping transports more than half of the total transported tonnage in Europe and its operations are close to shore, it is a major contributor to emissions in coastal areas. Causing health risks to humans and being a major contributing source of GHG emissions.

To reduce the impact of ship exhaust emissions, governments and international organizations place direct requirements on ships on both a regional and global level [DNV, 2021]. The International Maritime Organisation (IMO), is the most influential global regulator and has concrete ambitions for 2030 and 2050 [IMO, 2012] [MEPC72, 2018] [IMO, 2020]. The

European Union has its own ambitions and regulations on a regional level and included the maritime transport sector in its 'Fit for 55' package [EC, 2021]. New-built and existing ships, including short-sea vessels, will have to comply to these regulations. The main driver for the implementation of these regulations being health concerns [DNV, 2021]. Another driver for emission regulations for shipping may be protectionism. Regional emission regulations offer potential to form a barrier on a regional level by increasing transport cost and the increased capital intensity of low-emission ships.

Methods to comply to (future) emission reducing regulations have received much attention in research [IMO, 2020]. Several strategies offer solutions to shipowners on how to comply with emission-reducing regulations. These solutions consists of various fuel strategies, operational strategies and the addition of emission reduction systems on ships. All of these have various effects on the operation and profitability of ships. For example, some low-emission fuels require non-conventional fuel storage systems, which have specific requirements (e.g. location, volumetric, safety). Operational strategies, such as slow steaming, have the potential to significantly reduce emissions but decreases profitability. Furthermore, the addition of technical measures have impact on ship design, and effectiveness of specific systems depend on ship type, size and operational profile. In addition, uncertainties in, for example, fuel and carbon credit prices might have a significant effect on individual strategies. These considerations illustrate the complexity of choosing 'the right' cost-effective strategy for a specific ship.

The companies who finance ships are increasingly taking the emission profile of a ship into account when providing capital to shipowners. To reduce credit risk and the risk of stranded assets, financing parties require ships to comply to current emission regulations, and require ships to be ready for more stringent regulations in the future. As mentioned earlier, a variety of systems and strategies provide solutions to comply to these emissions regulations. Investigating the economic viability and technical feasibility of emission reducing strategies for specific ship types, sizes and operational profiles will support shipowners and financiers in making robust and cost-effective decisions in their efforts to reduce their emissions.

1.2. Air Pollution Regulations

Regulations and local policies are the main driver for emission reduction of the shipping sector, placing direct requirements on ships [DNV, 2021]. Shipowners are incentivised to reduce their emissions by both hard requirements and financial incentives related to the amount of emissions produced. The IMO is the most influential global regulator and has concrete ambitions for 2030 and 2050. In addition, the European Commission proposed regional regulations to reduce emissions of the maritime transport sector as part of their 'Fit for 55' package. The regulations and ambitions of the IMO and the European Commission are discussed consecutively in section 1.2.1 and 1.2.2 and their regulatory timeline is summarized in Figure 1.1.

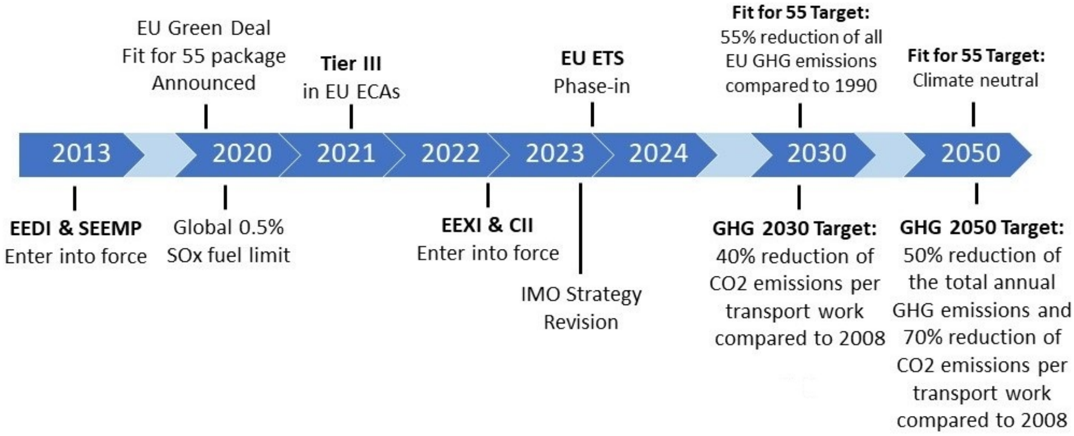


Figure 1.1.: The emissions regulatory timeline for ships, imposed by the European Commission (upper part) and the International Maritime Organisation (bottom part). (Data source: MEPC72 [2018], IMO [2020], IMO [2021b], EC [2021])

1.2.1. International Regulations (IMO)

The IMO has introduced a number of short and long term ambitions and regulations to reduce emissions from ships. The IMO's long-term ambition is to reduce total annual GHG emissions by at least 50% relative to to 2008 [MEPC72, 2018]. The IMO expressed its short-term ambition to reduce CO_2 emissions per transport work by at least 40% by 2030 relative to 2008 [MEPC72, 2018]. To achieve this short-term goal, several regulation have been introduced.

The IMO introduced the Energy Efficient Design Index (EEDI) for newly built ships with a weight of 400 Gross Tonnage (GT) and above from 2013 forward [IMO, 2012]. It expresses the energy efficiency level in grams per capacity mile of a specific ship given a specific ship type and size segment. Equation 4.1 shows that EEDI regulations incentives to increase capacity, and reduce CO_2 emissions with technical measures to achieve a better (lower) EEDI. In addition, speed reduction improves the EEDI. This seems counter-intuitive, however the power required, and thus fuel consumption and emissions, for propulsion is a function of the speed cubed [Lindstad et al., 2011]. Therefore, the CO_2 emissions are significantly reduced with a small reduction in speed.

$$\text{EEDI} = \frac{\text{CO2 emissions (based on theoretical fuel consumption)}}{\text{Transport capacity} \cdot \text{Ship speed}} \tag{1.1}$$

In addition, regulations are introduced for existing ships. All ships of 400 gross tonnage and above have to calculate their Energy Efficiency Existing Ship Index (EEXI) from 2023 forward. Furthermore, ships have to comply with a maximal carbon intensity index level of their ship type and size. The EEXI is a follow-up to EEDI regulations, but for existing ships. Therefore, the EEDI can be used as a substitute of the EEXI, where the EEDI index is lower than the EEXI requirement. The calculation of the EEXI (equation 1.2) is similar to the calculation of the EEDI and gives the same incentives; increase capacity, reduce speed and reduce CO_2 emissions with technical measures.

$$\text{EEXI} = \frac{\text{CO2 emissions (based on theoretical fuel consumption)}}{\text{Transport capacity} \cdot \text{Ship speed}} \tag{1.2}$$

Furthermore, regulation are introduced to improve ship operations and reduce carbon emissions per transported ton/mile. The Ship Energy Efficiency Management Plan (SEEMP) was introduced in 2013, a ship-specific plan to improve the energy efficiency of a ship [IMO, 2020]. It applies to all existing vessels of 400 GT and above. In addition, ships of 5000 GT and above have been required to report their annual fuel consumption to their flag State.

As a follow-up to the SEEMP regulations, ships of 5000 GT and above are required to calculate their Carbon Intensity Indicator (CII) from 2023 forward. The CII requires changes on the operation of the ship to improve energy efficiency over time. The CII (equation 1.3) is calculated annually and stimulates the efficient transport of freight. It incentives existing ships to reduce CO_2 emissions through technical measures, retrofit the vessel during its lifetime, switch to low-carbon fuels, increase capacity, or improve operational efficiency.

$$\text{CII} = \frac{\text{CO2 emissions (based on actual fuel consumption)}}{\text{Transport capacity} \cdot \text{Distance travelled}} \tag{1.3}$$

Furthermore, the IMO also introduced voluntary performance indicators, such as the Energy Efficiency Operational Indicator (EEOI). This indicator show the ship's CO2 emissions in relation to its operational activities, similar to the CII calculation but using cargo mass instead of capacity Deadweight Tonnage (DWT) [Parker et al., 2015].

In addition to carbon emissions regulations, the IMO also introduced measures to reduce other airborn emissions produced by ships. Sulphur (SO_x) emission regulations incentivises ship operators and owners to invest in exhaust gas cleaning systems, use of low-sulphur fuels or change to alternative fuels. From 2020 all ships worldwide are required to use fuel containing no more than 0.50% sulphur. In European Emission Control Area's (ECAs), a more stringent SO_x limit of 0.10% is in effect from 2015. Nitrogen Oxide (NO_x) emissions requirements by the IMO for marine diesel engines were introduced in 2021 by Tier III requirements for ships operating in ECA and Tier II for ships operating outside European ECAs. Tier III & II NO_x standards requires a specific value for gNO_x/Kwh based on the engine's rated speed. For a diesel engine to comply to IMO Tier III regulation NO_x emissions have to be reduced, which requires installations of a Selective Catalytic Reduction (SCR) system.

The IMO's mid- and long term emission regulations are not yet known and will be agreed upon in the period 2023-2030. These regulations may include other operational energy efficiency measures not included in the short-term measures such as the use of low-carbon fuel, alternative propulsion systems and other regulations that incentives GHG reduction.

1.2.2. Regulations in the European Economic Area

In addition to the global regulations set by the IMO, regional regulations are also introduced for the European Area. On July 2021 the European Commission adopted legislative proposals to reduce GHG emissions as part of the European Green Deal 'Fit for 55' package [EC, 2021]. From 2018 forwards, ships of 5000 GT and above are required to monitor and report their CO_2 emissions. Furthermore, from April 2019 ships are also required to submit an emission report for each ship which performed transport activities in the European Economic Area. This provides data on which regulators can base future regulations.

Along with providing data, the European Commission also include CO_2 emissions from ships of 5000 GT and above in the European Emissions Trading Scheme (EU ETS) from 2024. In practice this means that shipping companies will have to purchase EU Allowances (EUA), which permit the emission of one tonne of carbon dioxide equivalent [EC, 2003]. This will apply to 100% of emissions between EU ports and 50% of emissions from an EU port to an non-EU port and vice versa [KVNR, 2022b]. The regulations will have a two year initial phase-in period in which only a part of the emissions are covered, reaching 100% after three years. In 2025, 2026 and 2027, the verified emissions must be covered for consecutive 40%, 70% and 100% [KVNR, 2022b]. These proposals incentives shipping companies to reduce CO_2 emissions. Shipping companies have to make a trade-off between the cost of ETS and the cost of alternative fuels and other technical and operational measures. A provisional agreement on these proposed regulations was agreed in November 2022 and will be finalized in the first half of 2023 [KVNR, 2022a]. Furthermore, it is expected that from 2027 ships of 400 GT and above will be included in the EU ETS [KVNR, 2022a].

The long-term emission regulations for the European Area are unknown [KVNR, 2022a]. However, the European Commission has set its long-term ambition to be climate neutral by 2050. This report considers a time frame of approximately 10 years from now and therefore these long-term objectives are less relevant.

1.3. Background NESEC and Short-Sea Shipping

This report is realized in collaboration with the ship finance company Nederlandsche Scheepsbouw Export Centrale (NESEC). Since its foundation in 1946, NESEC has been promoting the development and innovation of shipbuilding in the Netherlands. NESEC's current activities mainly consist of providing primary mortgage loans for both new-build and second-hand vessels, targeting Dutch and Northwest European shipowners within the short-sea shipping sector.

Short-sea shipping is defined as "the movement of cargo and passengers by sea between ports situated in geographical Europe or between those ports and ports situated in non-European countries having a coastline on the enclosed seas bordering Europe" [EC, 1999]. The transport capacity of these vessels is often less than 15,000 DWT, which is relatively small compared to deep-sea vessels. However, despite its small vessel size, the short-sea sector accounts for more than half of the total tonnage of total maritime transport in Europe [Eurostat, 2022]. In addition, short-sea shipping is an important segment within Dutch shipping sector due to the strong presence of Dutch shipowners in the short-sea [Corres, 2013].

The short-sea vessels financed by NESEC must comply with the emission regulation introduced by the IMO and the European Commission as discussed in sections 1.2.1 and 1.2.2. To reduce credit risk and the risk of stranded assets, NESEC requires ships to comply to current emission regulations, and requires ships to be ready for more stringent regulations in the future. Comparing the economic viability and technical feasibility of emission reducing strategies for specific ship types provides insights and supports NESEC in making sound investment decisions.

1.4. Research Problem Statement

Ships have to comply to increasingly strict regulations regarding emissions and energy efficiency, as discussed in sections 1.2.1 and 1.2.2. Shipping companies and operators are free to choose the most optimal solutions to comply with these regulations. There are several technical, operational and fuel strategies that offer solutions to comply with emission-reducing regulations. All of these have various effects on the operation and costs of ships. In addition, the effect of emission reduction strategies on fuel cost, EU ETS cost, the vessel's income, and the technical feasibility of individual strategies depend on ship type, size and operation. Investigating the economic viability and technical feasibility of emission reducing strategies for specific ship types, sizes and operational profiles will support shipowners and financiers in making robust decisions in their efforts to reduce their emissions.

1.4.1. Problem solution criteria

From the specified research problem, several criteria can be identified that have to be taken into account to achieve a viable solution. First of all, a selection of emission mitigation measures have to be specified from literature. Thereafter, feasibility of measures on specific vessel types and sizes has to be determined. To provide solutions, cost-effectiveness of measures are compared under the constraints of regulatory compliance for a set of technical and operational ship inputs. Where "cost" relate to the financial feasibility of solutions and "effectiveness" relates to the effect of measures on regulatory compliance of vessels. From the specified research problem in sections 1.1, 1.2 and 1.3, and the general solution description, several solution criteria are identified.

The solution must meet the following conditions:

- The solution must apply to (existing) short-sea vessels under 15,000 DWT.
- Take make a unbiased comparison, all relevant emission mitigation measures: technical, operational and low-emission fuels, must be included.
- The technical feasibility of solutions must be taken into account to provide implementable solutions.
- The solution generation methods should be based on a set of ship inputs, as technical and operational characteristics vary from ship to ship.
- The solution must provide insight into costs of EU allowance for specific ships, to support shipowners in making informed investment decisions to reduce carbon emissions.

- The solution must determine the effect of emission mitigation measures on regulatory compliance of specific ships for the EEXI and CII.
- The solution must compare the financial viability of solutions, to support shipowners in making informed investment decisions to reduce CO2 emissions.
- The solution must provide insight into the solution's reliance on pricing assumptions in the approaches used, to quantify the uncertainty in the financial viability of solutions. This supports shipowners in making robust investment decisions.

These solution criteria determine the literature search criteria that form the basis of the literature review for methods for comparing emission mitigation measures.

1.4.2. Literature search criteria and review

To conduct a systematic review of scientific publications, literature search criteria have been specified with regard to the comparison of cost-effectiveness of emission mitigation measures on ships. These criteria follow from the problem solution criteria.

The following words or their combinations are used as keywords for the literature review: energy efficiency, carbon emissions, low-emission marine fuels, emission reduction, ship owner, comparison, carbon intensity and impact assessment.

The literature has been filtered and selected for relevance to the solution criteria of this research. In addition, to avoid unverified data, peer-reviewed journals and research reports have mainly been used as the sources of information. This poses a challenge, as most research on this topic is published as an non-scientific (news) articles by classification societies, or by consultancy companies. These sources provide very little information of methods used.

The high level literature review on comparison models and methods is presented in Table 1.1. This shows that no single research meets all problem solution criteria. It can also be noted that the list of reviewed studies is quite small, with only seven studies presented (Tab. 1.1). In the current literature, there is little research that combines multiple solutions (technical, operational, alternative fuels) and considers their effect on regulatory compliance.

Research	Low-emission fuels included	Technical measures included	Operational measures included	Ship types considered	Emission regulations considered	Cost comparison included	Feasibility requirements included
Smith [2012]	No	No	Yes	200,000 dwt Tanker	EEDI	Yes	Yes
UMAS [2016b]	Yes	No	No	35–60,000 dwt bulk carriers	EEDI	Yes	No
UMAS [2017]	Yes	Yes	Yes	60-100,000 dwt bulk carriers	n/a	Yes	Yes
DNV [2021]	Yes	Yes	Yes	not limited	n/a	Yes	n/a
Lindstad et al. [2022]	No	Yes	Yes	63,000 dwt bulk carriers	EEOI	Yes	Yes
IMO [nd]	No	Yes	Yes	not limited	EEDI, EEOI	Yes	Yes
Schroer et al. [2022]	No	Yes	Yes	33-125,000 dwt container vessel	EEDI, EEXI, CII	Yes	No

Table 1.1.: List of reviewed studies that relate to the problem solution criteria

1.4.3. Research gap

From the literature review in Table 1.1 several gaps in the literature can be identified. Most research considers deep-sea vessels, larger than 35,000 DWT. This is understandable as CO_2 reduction of large ships has a greater impact on CO_2 reduction of the shipping sector as a whole. However, the (future) regulation described in 1.2.1 and 1.2.2 also apply to smaller short-sea vessels (15,000 DWT or smaller). Moreover, research on the reduction of emissions in the short-sea sector is important as short-sea shipping is a significant sources of emissions. The short-sea sector accounts for over 60% of sea transport of goods (in tonnes) to and from European ports [Eurostat, 2022], and its emissions are close to urban areas. Furthermore, the majority of present day research does not compare all relevant emission mitigation strategies for existing vessels; technical, operational and low-emission fuels. Moreover, several studies present case studies on how to comply to EEOI and EEDI, however little research focused on strategies for vessels to comply with EEXI and CII. In addition, no study has looked at the impact of the introduction of EU allowances on short-sea ships, which is particularly relevant as these vessel mainly operate between European ports.

To clearly define the research gap, a detailed description is presented of the comparison methods most closely related to the problem solution criteria. Of the various techno-economical modelling tools and methods in Table 1.1 the comparison methods that meets the requirements of problem solution criteria best are the Appraisal tool by the IMO and the GloTraM model. A summary of the purpose and comparison methods of these two models, with the identified research gaps, is presented in Table 1.2. The following text provides additional background information on the Appraisal tool and GloTraM model.

Research by IMO presents a computer-based model to appraise the technical and operational energy efficiency measures for ships, the so called 'IMO Appraisal tool' [IMO, nd]. This tool calculates the effect of technical and (some) operational emission mitigation measures on the EEDI and EEOI. Furthermore, it compares cost-effectiveness of individual measures. The tool presents a marginal abatement cost curve, showing the cost of reducing one more tonne of CO_2. A free version of the tool can be downloaded online, and the user can obtain results based on two ship inputs: ship type and transport capacity. The advantage of this tool is that it presents a clear overview of the effect of measures on regulatory compliance and it provides insights in their financial viability. An additional advantage is the simple and user-friendly interface in MS Excel. The disadvantages of the model are the lack of documentation of the methods used, the low accuracy and non-ship specific results, as calculations on carbon reduction and cost of measures are based only on inputs for ship type and capacity.

The second model most closely related to the problem solution criteria is the GloTraM (Global Transport Model) model. The model is developed to analyse future scenarios of the shipping sector to assist in informed decision making for investments in emission reducing measures. The model also provides insight into broad scenarios with regard to fleet and market developments, fuel developments, scrapping rates and the effect of regulations on the shipping sector. The tool was developed by the RCUK Energy programme lead by the UCL Energy Institute and industry (Shell, Lloyd's Register, BMT and Rolls-Royce). Several publications have been produced using the GloTraM model, using various scenarios specified by clients: [LloydsRegister, 2013], [UMAS, 2016b], [UMAS, 2016a], [IMO, 2016] and [UMAS, 2017]. These publications give general outlines of the tool for specific scenarios, but do not specify detailed assumptions and methods of the model as a whole.

Model name	**Purpose and comparison methods used**	**Research gap**
Appraisal Tool [IMO, nd]	Low detail comparison of cost-effectiveness of a selection of technical and operational emission reducing measures based on inputs: ship type, capacity and fuel prices using MS Excel. In addition, the effect of individual measures on the EEDI and EEOI are specified.	The model does not include all available measures, such as operational measures and low-emission fuel strategies. The tool does not take the operational profile into account. The tool does not present the effect of measures on CII and EEXI compliance.
GloTraM [UMAS, nd]	Techno-economic model of the global shipping sector to generate scenarios for the evolution of the shipping sector. Among other things, the model evaluates investments in main machinery, alternative fuels, energy efficiency technologies and operational speeds using a NPV method.	The tool considers mainly large vessels (60,000 DWT+). The tool does not present the effect of measures on CII and EEXI compliance. Several publications give general outlines of the tool for specific scenarios, but do not specify detailed assumptions and methods of the model as a whole.

Table 1.2.: Summary of the purpose and comparison methods of comparison models most closely related to the problem solution criteria of this study, with specified research gaps (Source: own source)

Scope

The aim of this research is to fill these gaps in knowledge by comparing all feasible CO_2 reducing measures for short-sea ships below 15,000 DWT from a shipowner/operators perspective. The second aim is to provide a techno-economical model which calculates the

EEXI and CII for a set of ship characteristics and determines which fuel strategy or emission reducing measures are viable for this vessel, taking into account the impact on the ship design. Since the EEXI, CII and EU ETS regulations only cover CO_2 emissions, only this ship pollutant is addressed in this study. The scope further comprehends the retrofitting of existing vessel, although the methods in this report can be used for new-build vessels as well. The technical feasibility of CO_2 mitigation measures is determined by formulating technical requirements of individual systems constraint's (e.g. weight, space, power etc.) and comparing these to a number of representative example vessels. The CO_2 saving potential of systems and strategies are calculated from a tank-to-wake perspective. This was chosen because the EU and IMO regulations are based on tank-to-wake emissions [IMO, 2012] [IMO, 2020] [EC, 2021].

Furthermore, a price sensitivity study is performed to analyse the uncertainty in financial viability of the various emission mitigation measures. As financial viability of solutions highly depends on fuel, EU ETS en time charter price assumptions.

1.4.4. Research Objective and Research Question

This research presents a tool to compare cost-effectiveness of strategies for short-sea vessels to reduce their carbon emissions. Where "cost" refers to the financial viability of solutions and "effectiveness" refers to the CO2 reduction potential of measures, and the solutions they provide to comply with EEXI and CII regulations.

The research objective of this report is as follows:

"*To compare techno-economical aspects of solutions for technical feasibility and financial viability for short-sea vessels below 15,000 DWT within the constraints of compliance with current and future IMO and EU carbon emission regulations.*".

The literature gaps to be addressed can be condensed to the following research question:

How to assess viable solutions for short-sea vessels below 15,000 DWT to ensure compliance with current and future IMO and EU carbon emission regulations?

To answer the main research question, three sub-questions are formulated, which are:

1. What emission mitigation measures are available for ships?
2. What requirements must an emission mitigation measures meet in order to be technical feasible on short-sea vessels below 15,000 DWT?
3. How can cost-effectiveness of measures/strategies be best compared?

1.5. Report outline

Chapter 2 presents a literature study on emission mitigation measures available for short-sea ships. The measures are subdivided in technical, operational and fuel strategies. For each measure the technical requirements (e.g. weight, space, power etc.) that determine its technical feasibility are specified. In addition other relevant and practical implication of individual measures are summarized. Furthermore, Chapter 2 presents an analyses of the short-sea shipping sector in Europe. A selection of reference vessels that characterise the short-sea fleet is made. Thereafter, the technical applicability of emission mitigation measures is determined by comparing these to the requirements identified previously. Additionally, the effect of operational constraints on the measures emission reduction potential are specified.

With the specified applicability, feasibility and emission reduction potential of measures for specific ship types and size from Chapter 2, a comparison method can be selected. Chapter 3 explores comparison methods based on literature. An appropriate comparison approach is selected and the overall framework of the Comparison Tool is defined.

Chapter 4 presents the main calculation methods and assumptions of the Comparison Tool. In addition, verification and validation of the model is performed.

Chapter 5 presents results from the Comparison Tool for a case study for a selection of representative short-sea vessels. The financial viability and effect of individual measures on regulatory compliance are presented. Moreover, results of a sensitivity study for several fuel price, CO_2 price and TCE price scenarios are offered.

A discussion of the results and recommendations for future research are presented in Chapter 6. Lastly, the conclusions of the report are presented in Chapter 7.

2. Emission mitigation strategies available for short-sea ships

This chapter describes the state-of-the-art emission mitigation measures that are considered relevant for the Comparison Tool. Several emission mitigation measures for ships have been presented in literature. An overview of these emission reducing measures available for ships is presented in section 2.1. Additionally, the technical requirements that determine feasibility of a measure (e.g. weight, space, installed power, etc.) and technology readiness level are specified for each measure. In addition, the effect of operational constraints on the measures carbon reduction potential are specified.

Furthermore, an analyses of the short-sea shipping sector in Europe is presented in section 2.2. A selection of reference vessels that characterise the short-sea fleet is made and their technical characteristics are presented. After which the technical applicability of emission mitigation measures is determined.

2.1. Emission mitigation strategies

Various emission mitigation measures for ships have been presented in literature, which can be roughly divided into four methods based on their method of CO2 reduction [Rehmatulla et al., 2017].

- Improving energy efficiency using cost-effective technical and operational measures, normally resulting in a reduction in fuel consumption.
- Using renewable energy sources e.g. solar energy or wind propulsion.
- Using fuels with a lower carbon content .
- Emission removal/reduction technologies e.g. carbon capture devices.

Another method of subdividing carbon mitigation measures is by their impact on the vessel [Xing et al., 2020], which subdivides the measures into three types; technical measures, operational measures and using low-emission fuels. This classification method is suitable for this study as it makes a similar classification in technical and operational improvements as the EEDI/EEXI and CII regulation.

A selection of emission mitigation measures for short-sea ships is presented in Figure 2.1 based on the following studies. Operational and technological measures are given by Wang et al. [2010], UMAS [2016a] and Armstrong [2013]. CO_2 reduction strategies by using alternative fuels are described by Halim et al. [2018], DNV [2015]. Reviews of ship energy efficiency research and technologies are made by Bouman et al. [2017], Xing et al. [2020], Al-Enazi et al. [2021] and Jimenez et al. [2022], which provide an overview of state- of-the-art research on this topic.

All available measures for ships are discussed uniformly for their general characteristics and key aspects that determine feasibility. Feasible in this report means that a measure can be implemented from a practical perspective, considering key aspects such as space and weight requirements and technology readiness level. All measures are described in a uniform way to make a fair comparison. A selection of applicable measures for short-sea ships is presented in Figure 2.1. Measures and fuels that are not shows in Figure 2.1 are not considered feasible for short-sea vessels and are also discussed.

The technical measures, operational measures and low-emission fuels and are discusses successively in section 2.1.1, 2.1.2 and 2.1.3.

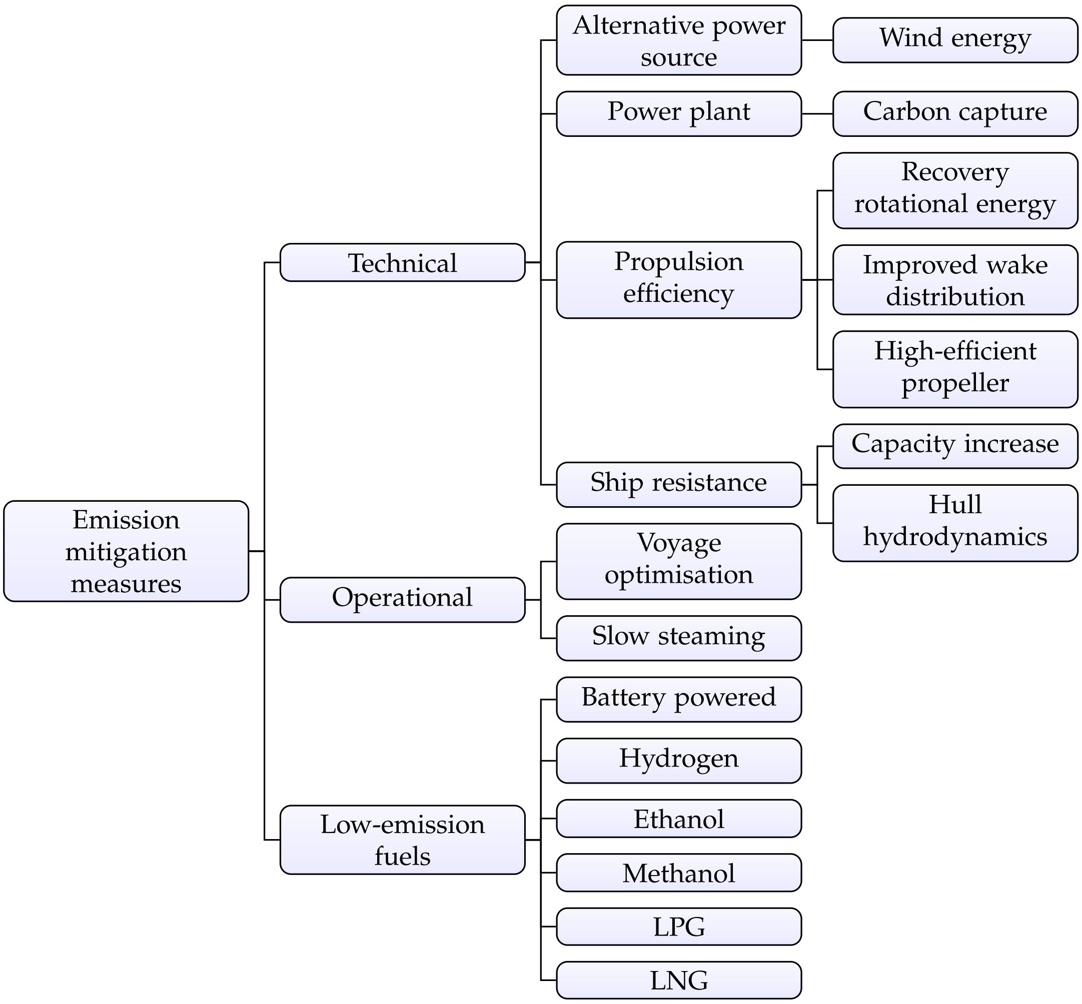


Figure 2.1.: Selection of emission mitigation measures for short-sea shipping. (Source: Armstrong [2013], DNV [2015], UMAS [2016a] Xing et al. [2020])

2.1.1. Technical measures

A technical measure measure reduces a ship's carbon emissions compared to its original design by reducing energy consumption, or by capturing the carbon emitted. Some of these technologies can be retrofitted to ships, but some technologies have such an impact on ship design that this is not feasible.

The technical measures are divided into the four subcategories: ship resistance, propulsion efficiency, power plant and alternative energy sources and are discussed successively.

Ship resistance

Reducing the ship hull resistance reduces fuel consumption and thus CO_2 emissions. A range of technologies are available to improve hull hydrodynamics. Certain rudder types improve energy efficiency by recovering rotational energy by a twisted edge [Kim et al., 2014], or by reduced friction by a reduced rudder surface [wei Song et al., 2018]. Slender concept hull designs are proposed as a methods to reduce resistance [Lindstad et al., 2014] [Lindstad and Eskeland, 2015] [Tillig et al., 2015]. In addition, the hull can be made more slender by adding an extra midship section. This may increases resistance and thus reduces the ship's speed, but reduces emissions per tonne/mile by the increased transport capacity. To the authors best knowledge, no research is available on improving fuel consumption by the addition of a mid-ship section, although short-sea shipping companies have retro-fitted ships. Examples of these are vessel such as the 'Rotra Mare' en 'Rotra Vente'. Air lubrication reduces frictional resistance by pumping compressed air into a recess in the ship's bottom. The energy-reducing potential of this technology depends on the ship's size, speed and flatness of the ship's bottom [ICCT, 2011]. A ship's bows can be optimized by retro-fitting it with a bulbous bows, reducing wave resistance and added resistance [Yu et al., 2017]. This measure however is not always appropriate for small and slower vessels, and may cause increased resistance [OECD, 2018]. In addition, this measure is mostly applied to new-builds as lost income during retro-fit may outweigh the potential fuel savings [Rehmatulla et al., 2017]. Finally, ships can apply advanced hull coatings that reduce frictional resistance by increasing hull smoothness and limiting water growth [GloMEEP, ndb]. All of the above measures have no significant space requirements or have high technological readiness levels, and therefore all are considered feasible solutions for short-sea vessels.

Propulsion efficiency

The improvement of propulsion efficiency reduces energy demand, thus mitigating CO_2 emissions. Propulsion efficiency is expressed as the product of hull efficiency, propeller efficiency, relative rotational efficiency and shaft efficiency [Terwisga and Schuiling, 2017]. High-efficiency propellers can be retro-fitted on short-sea vessels, improving propeller efficiency. Efficiency losses due to the non-homogeneous inflow of water towards the propeller can be reduced by wake-equalizing ducts and nozzles, improving propeller efficiency. Pre-swirl and post-swirl devices reduce energy losses by recovering (rotational) potential energy [Shin et al., 2013]. In addition, the use of a Contra Rotating Propeller (CRP) is also a method to reduce rotational energy losses. All of the above measures have no significant space requirements or have high technological readiness levels, and therefore they are all considered feasible solutions for short-sea vessels.

Power plant

A number of methods are available to reduce energy losses in the main engine and auxiliary engines. Due to the shorter routes nature of the short-sea sector, the demand for propulsion power varies as vessels travel shorter distances at a constant speed [DNV, 2021]. Therefore, flexible power systems such as diesel electric propulsion and power take off/in configurations have potential to decrease fuel consumption [Dedes et al., 2016] [Ling-Chin and Roskilly, 2016] [Lebkowski, 2018]. This measure requires additional space in the engine room for the installation of PTI/PTO systems, and space for energy storage systems. The technology readiness level of these systems are high, and therefor these are considered feasible solutions for short-sea vessels.

CO_2 capture and storage is a method to lower carbon intensity of ships. Additionally, these systems offer solutions to lower sulphur emissions and therefore allow ships to use high sulphur fuel oils in ECAs. These systems require space behind or next to the exhaust funnel for the installation of the system [ValueMaritime, nda]. Additionally, space is required for two containers, in which the captured CO_2 is stored. Although this technology is relatively new, it is a proven technology with several short-sea vessels already equipped with these systems [ValueMaritime, nda]. From a practical viewpoint, shipping companies indicate that opting for ULSFO instead of scrubbers is influenced by the the uncertainty of availability of HFO in the future, as low-sulphur fuel oil become the standard.

Furthermore, various energy-reducing measures for a ship power plant are described in the literature, but these are considered unfeasible solutions for short-sea vessels. These systems are briefly described. Thermal energy losses through exhaust gasses can be reduced by Waste Heat Recovery (WHR) systems [Larsen et al., 2014] [Mondejar et al., 2018]. WHR, however, is only effective on large ships with main engine power higher than 20,000 kW and auxiliary engine power higher than 1,000 kW [ICCT, 2011]. Increasing fuel efficiency by improving auxiliary systems such as heat exchangers, lighting, HVAC, filters, condensers (etc.) are not considered in this report as fuels savings for these systems are minimal, well below 1% [ICCT, 2011]. Shore power can reduce emissions in port [IMO, nd], however this systems is only feasible on trades with shore connection facilities in port and therefore this measure is not considered feasible for a general vessel.

Alternative power sources

Wind Assisted Propulsion Systems (WAPS) reduce power demand, and thus fuel consumption and emissions. WAPS such as wings and flettner rotors are ready available systems which can be retro-fitted on existing vessels. These systems require space on deck and require space around the device to limit air-flow interference with other objects. Because wings and rotors are well developed and proven technologies, they are considered feasible solutions for short-sea vessels [Clodic et al., 2019]. Fuel saving potential for WAPS varies and is highly dependent on the ship's operational profile; area of operation and speed [Groot, 2022]. Additionally, research by Lindstad et al. [2022] shows that at lower speed (10kn) WAPS effectiveness in saving fuel increases significantly. Which is beneficial, as short-sea ships operates at relatively lower speeds.

Kites are also proposed as a wind propulsion device in research, however due to low technology readiness level these are considered unfeasible for short-sea vessels [ICCT, 2011] [Clodic et al., 2019]. Furthermore, solar panels can provide energy savings on ships. These systems, however, require large deck-space to be effective and are therefore not applicable to typical short-sea vessels transporting general cargo, dry-bulk, containers.

Conclusion

Technical emission mitigation measures are compared for their applicability for the use in short-sea vessels, of which Table 2.2 presents an overview. Furthermore, detailed information on the space and location requirements are presented in Appendix K.

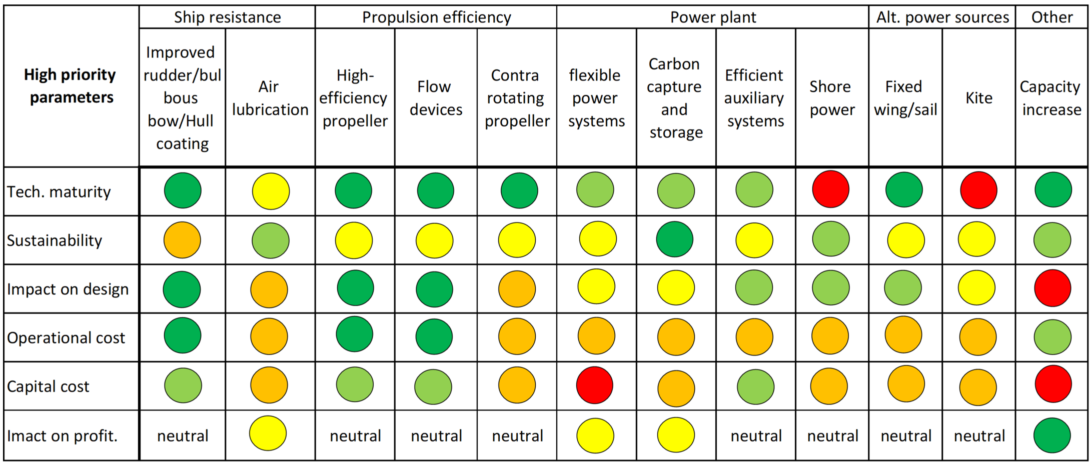


Figure 2.2.: Comparisons of technical measures, and their applicability to short-sea vessels. With the green color indicating a high or positive impact, and a red color indicating a low or negative impact. (Sources: based on various sources in this chapter)

2.1.2. Operational measures

Operational solutions to reduce CO2 emissions from ships mainly consist of efforts to reduce fuel consumption. Suitable options are divided in four categories; slow steaming, voyage optimisation, maintenance optimisation and human factors and are discussed successively.

Slow steaming

Slow steaming reduces emissions by operating below the design speed of the vessel. It provides an efficient operational measure to lower carbon emissions, and large $C0_2$ reductions can be achieved[ICCT, 2011]. When a ship decreases its speed, fuel consumption decreases approximately with a power of three, hence decreasing fuel cost per ton-mile [Lindstad et al., 2011] [CE, 2012]. Furthermore, slow steaming does not require large capital investment and can be applied on all ships. However, potential profitability of ships decreases as less cargo is transported for a given time-frame. Since this measure has no technical requirements, it is considered a feasible solution for short-sea vessels.

Voyage optimisation

Voyage optimisation comprehends optimizing speed and routes under the constraints of weather conditions and defined port time windows [Wang et al., 2010]. Reducing the ship's speed and arriving 'just in time' is an effective measure, similar to slow steaming. Additionally, weather routing has a significant energy reduction potential [ICCT, 2011]. However, this measure might be less effective for short-sea vessels due to their short-distance nature and their operation in coastal waters, limiting their route options. Furthermore, the emission reduction potential of weather routing varies and is highly depended on the ships area of operation [Groot, 2022]. In addition, trim and ballast optimisation has the potential to reduce fuel consumption by reducing hull resistance[GloMEEP, ndd].

All voyage optimisation have no technical requirements and are therefore considered feasible solution for short-sea vessels.

Maintenance optimisation

Maintenance optimisation such as periodic cleaning of the hull, and regular maintenance of machinery reduce fuel consumption [ICCT, 2011]. Fouling on the hull and the propeller increase resistance, which can result in significant energy losses. Although this measure can reduce emissions from a poorly maintained ship, it is difficult to determine its energy saving potential as a significant part of the world fleet already applies this measure [ICCT, 2011]. Therefore, maintenance optimisation is not considered applicable for a general short-sea vessel.

Human factors

The management of the ship by the crew determines whether the systems on board are used efficiently, thus minimizing energy consumption [Poulsen et al., 2022]. In addition, human efforts drive the implementation of energy efficient measures. Well-trained crews in the efficient use of systems may reduce fuel consumption and thus lower emissions [Poulsen et al., 2022]. Although this measure has emission reduction potential, it is not considered applicable for a general short-sea vessels as it is difficult to determine its energy reduction potential.

Conclusion

Operational emission mitigation measures are compared for their applicability for the use in short-sea vessels, of which Table 2.3 presents an overview. Slow steaming and voyage optimisation (just in time arrival, trim and ballast optimisation and weather routing) provide solutions to lower emissions from ships, without large capital investments. Moreover, these measures can be applied without any technical requirements being imposed on the ship design.

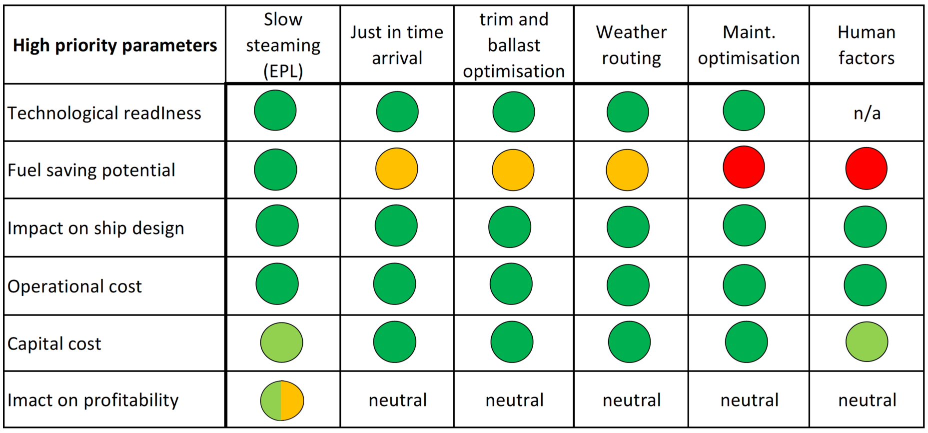


Figure 2.3.: Comparisons of operational measures, and their applicability to short-sea vessels. With the green color indicating a high or positive impact, and a red color indicating a low or negative impact. (Sources: based on various sources in this chapter)

2.1.3. Marine fuels

This section gives an overview of conventional and alternative fuels available for ships. Low-emission fuels provide solutions to lower carbon emissions significantly on the long term [DNV, 2019a]. Currently, low-emission fuels are used on less than 1% of all short-sea vessels in operation [Speight, 2011] [DNV, 2021] and new-build short-sea vessels with alternative fuel systems are mainly fully battery powered and non-cargo vessels [DNV, 2021]. This can be explained by multiple challenges associated with the implementation of alternative fuels, related to storage space and systems, technological maturity, energy cost, availability and toxicity.

This section discusses marine fuels, or energy carriers, for a set of parameters that determine whether a fuel is feasible on short-sea vessels. The priority parameters are; the required fuel storage space and weight, the technological maturity of fuel systems, the emission reduction potential and the availability of fuels [DNV, 2019a] [DNV, 2021]. Other key parameters are the flammability, toxicity and impact on the ship design [DNV, 2019a]. In this report the emission reduction potential for each fuel is considered from a tank-to-wake perspective, as the IMO emission regulations are also based on this [MEPC72, 2018] [IMO, 2021a]. There is therefore no difference in emissions between a gray or green alternative fuel.

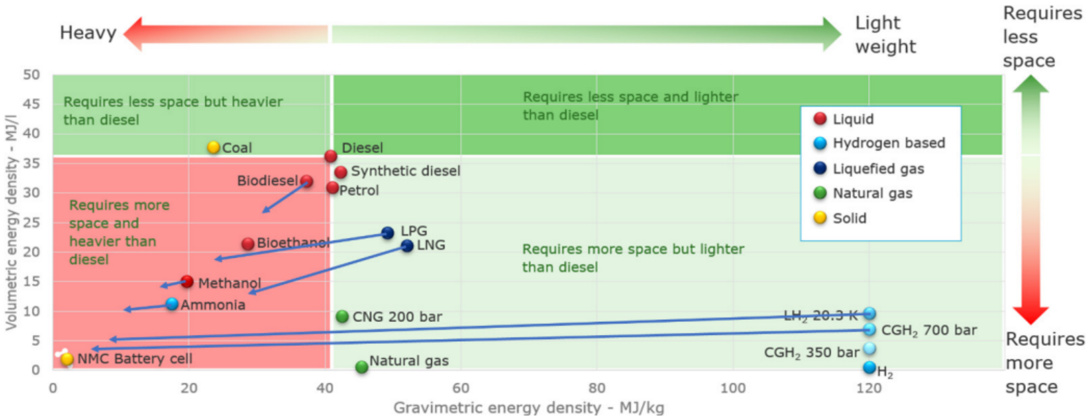


Figure 2.4.: Energy densities for different energy carriers, the arrows indicated the impact on density when taking into account the storage systems for the different types of fuel (indicative values). (Source: DNV [2019a])

The required fuel storage volume is regarded as the most important constraint for the implementation of low-carbon fuels [DNV, 2019a]. Therefore this report focuses on the comparison of storage space needed for alternative fuels. Research by DNV [2021] also discussed design options for fuel flexibility of engine, for new-builds and conversions. Due to time-limitation comparing (fuel flexible) engine strategies is not included in the scope of this report.

Volumetric and gravimetric energy densities of fuels and the type storage systems determine how much space is required for a fuel system. Figure 2.4 compares these three parameters for conventional and alternative fuels and provides a conceptual impact of fuel system choice on ship design. The following sections discuss marine fuels for the previously discussed list of feasibility parameters.

Fossil fuel oils

Fuels oils are traditionally used as a marine fuel in marine combustion engines and a variety of fuel oils are available. Dependent if a vessel is sailing in an Emission Control Area (ECA), a vessel is required to use low sulphur fuel oil to mitigate SO_x emissions. Non ECA compliant fuels are heavy fuel oil (HFO), Marine Gas Oil (MGO), Marine Diesel Oil (MDO) and Low Sulphur Fuel Oil (LSFO), with a maximum mass by mass sulphur content of consecutively 3.5 %, 1.5%, 1.5%, 1.0%. Ultra Low Sulphur Fuel Oil (ULSFO) is ECA compliant and has a sulphur content of 0.1% or lower. ECA requirements can also be met by using an exhaust gas cleaning system or scrubber when burning fuel with a higher sulfur content. All fuel oils are stored as liquid in simple tanks at atmospheric pressure. Figure 2.4 compares energy densities of different marine fuels, which shows that diesel oil has both the highest volumetric and gravimetric energy density compared, making it the most practical marine fuel.

Methanol and Ethanol

Methanol (CH_3OH) and ethanol (C_2H_5OH) have the potential to be (net-zero) CO_2 emission free marine fuels. The carbon footprint of these alcohol-based fuels are dependent on their production method, which is based on: fossil fuels, biomass, or synthesised from renewable electric energy [Yao et al., 2017]. In addition, no SO_X are emitted, NO_X emissions are low and no particulates (PM) are emitted [Yao et al., 2017].

Both methanol and ethanol are liquid at atmospheric temperature and pressure and are both largely traded commodities. Another advantage is that handling, storage and bunkering are similar to conventional diesel systems [Yao et al., 2017]. Several companies provide systems to adjust engines from marine gas oil to methanol [Man, nd] [Wartsila, 2021], making it easier to retrofit a vessel during their lifetime. In addition, because alcohol-based fuel are miscible in water, it is far less hazardous to the environment [MoS, 2018] and is therefore allowed to be stored in integral tanks without a double hull requirement. Appendix B present all the relevant class regulations on the fuel storage on methanol and ethanol fuelled vessels. Disadvantages of methanol as a marine fuel is that it is toxic to humans and the specific energy per kilogram is approximately a factor 2.2 lower than marine gas oil. Meaning 2.2 times more fuel mass is needed for the same power output.

Ammonia

Ammonia (NH_3) has the potential to be a widely used carbon-free marine fuel in the future. For ammonia to be a low-carbon marine fuel, its production method should be low carbon. Ammonia is produced by combining hydrogen gas with nitrogen. Although CO_2 neutral (green) ammonia has greet potential, it is not yet produced anywhere [DNV, 2022].

Ammonia is transported as a liquid by compressing it to 0.8 Mpa at 20 degrees Celsius or cooling it to -33 degrees Celsius at atmospheric pressure [Al-Aboosi et al., 2021], increasing its volumetric energy density to approximately 1/4 of that of diesel (Fig. 2.4). It also has a narrow flammability range, lowering the risk of unintentional combustion [Al-Aboosi et al., 2021]. The fuel can be used in internal combustion engines with small modifications or used directly in fuel cells [Al-Aboosi et al., 2021]. A disadvantage of ammonia is that it is highly corrosive, causing damage to gaskets. In addition, in case of release of ammonia or hydrogen by a damaged valve, pipe or fuel cell a toxic, corrosive and explosive atmosphere would form. moreover, technology to use ammonia as a marine fuel does not yet exist [Man, 2020]. The first ammonia-fuelled engine is expected to go to market in 2024 [Man, 2020], but large-scale uptake is not expected to start until 2030 [DNV, 2022]. There is existing storage and handling infrastructure available in European ports, however bunkering infrastructure for ships is not in place [DNV, 2019a].

DNV [2021] discusses design amplifications of chosen fuel strategies. For a conversion to ammonia, sufficient storage space should be available on the aft deck are. Which is the most natural space to store ammonia, keeping the fuel away from cargo without affecting cargo capacity. This requires shipyards to deviate from its current standards with probably higher building-cost. DNV [2021] also adds that one way to limit the fuel storage space needed is to evaluate the possibility for shorter bunker intervals.

LNG

liquefied natural gas (LNG) is the most-used alternative fuel in terms of current usage, and may offer a significant reduction in CO_2 emissions [Balcombe et al., 2019]. NO_x emissions are reduced up to 80% and SO_x and PM are almost eliminated compared to HFO [DNV, ndb]. Another advantage of LNG compared to methanol and ammonia is its higher volumetric energy density (Fig. 2.4). LNG has approximately 1/3 of the volumetric energy density of diesel when taking into account of storage systems. LNG is widely available all over the world and can be used on a large scale as marine fuel in the short term. A major disadvantage of LNG is its methane emissions during fuel production and engine slip, which acts as a strong GHG. This is because methane is a 120 times stronger GHG (per gram emitted) than CO_2 in terms of climate forcing [Lowell et al., 2013]. Using LNG as a marine fuel also requires additional systems to keep LNG liquefied at -163$^\circ C$ (at atmospheric pressure) which increase the cost of the propulsion system [Chorowski et al., 2015]. New pressurized systems also allow LNG to be transported at less cold temperature [DNV, ndb]. LNG is available in ports, however dedicated infrastructure to bunker ships is limited but improving rapidly in the North sea and Baltic area [DNV, 2019a].

LPG

Liquid Petroleum Gas (LPG) is a mixture between propane and butane, and is a by-product of oil gas refinery and production. LPG can also be produced sustainably, for instance as a by-product of renewable diesel production [DNV, 2019a]. Limited data is available on emission reduction potential of LPG, however estimates give a NO_x reduction of 10–20% compared to HFO, almost no SO_x emission, large reduction of PM and black carbon emissions and an overall greenhouse gas emissions reduction of 17% [DNV, 2019b]. The storage systems of LPG require 2-3 times the volume of oil tanks due to its lower volumetric energy density. The fuel is stored in cylindrical tanks at -42 degrees Celsius at atmospheric pressure or 8.4 bar at 20 degrees Celsius [DNV, 2019a]. Storage and handling facilities are available around the world, however bunkering infrastructure for ships is not available [DNV, 2019a].

Hydrogen

Hydrogen can be used as a marine fuel in combustion engines or in a fuel cell. The main advantage of hydrogen as a marine fuel is that it has near zero emissions and is carbon neutral when made from renewable energy. However, due to high cost of storage systems and fuel, it is not widely implemented on cargo vessels [DNV, 2019a]. Currently, there are no storage or bunkering infrastructure facilities developed in European ports [DNV, 2019a].

Hydrogen is stored as a liquid at -253 degrees Celsius or as a compressed gas up to 700 bar. Figure 2.4 shows that volumetric energy densities of both liquid and compressed hydrogen are very low, approximately 1/7 of that of diesel. This has major consequences for vessel layout and transport capabilities, because more storage space is required.

Battery powered

Battery powered ships have to potential to be zero-emission alternative. However, due to the high weight, large volume requirements, high investment cost and long charging time this energy storage option is not widely implemented in the shipping sector. Battery technology is well developed and ready to use on ships [DNV, 2019a]. On-shore power supply is available, however shore-based infrastructure to charge ships is not available [DNV, 2019a]. However, the European commission proposed regulations that obliges European ports to have shore power infrastructure available for ships [EU, 2022].

Conclusion

Conventional and alternative fuels are compared for their applicability for the use in short-sea vessels, of which Table 2.5 presents an overview. Detailed information on the space and location requirements for alternative fuels are presented in Appendix M. The technology readiness levels for fuel production, storage systems, energy converters, and process systems per fuel are included in Appendix L. Regulation concerning the storage of alternative fuels and energy storage systems onboard of ships are presented in Appendix B.

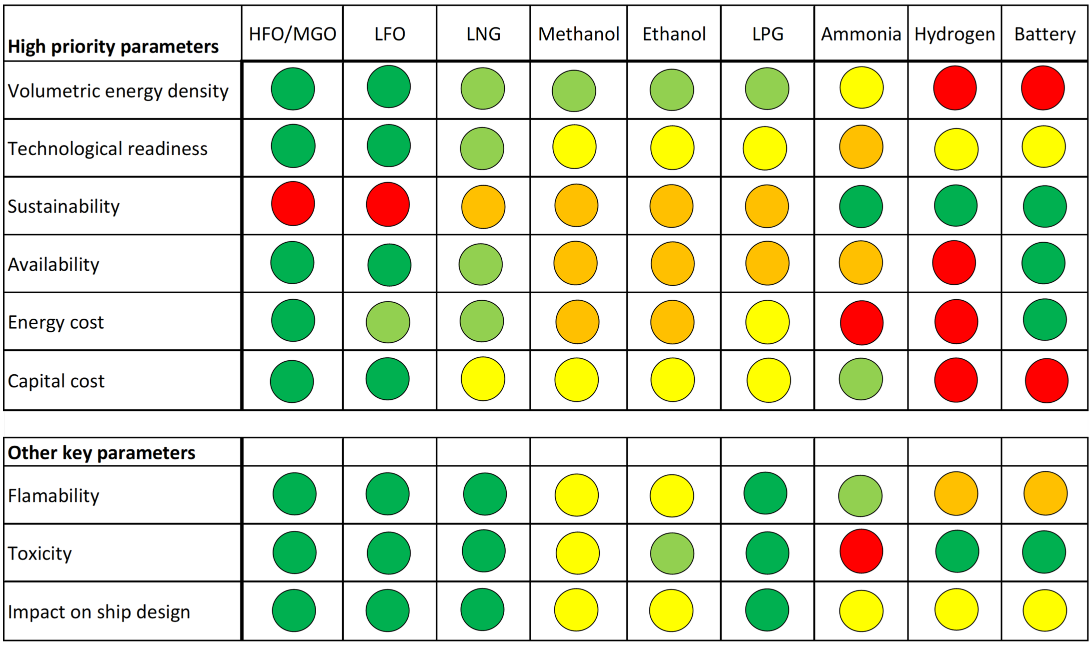


Figure 2.5.: Comparisons of available (grey) alternative and fossil fuels, and their applicability to short-sea vessels. (Sources: based on various sources in this chapter)

2.2. Short-sea shipping characteristics

This chapter introduces a market analysis in which short-sea vessels are discussed for their operational profile and general characteristics. With this information, requirements for emission mitigation measures are determined. After which the technical applicability of emission mitigation measures is determined.

2.2.1. Short-sea shipping market analysis

Short-sea shipping is defined as "the movement of cargo and passengers by sea between ports situated in geographical Europe or between those ports and ports situated in non-European countries having a coastline on the enclosed seas bordering Europe" [EC, 1999]. Short-sea vessels operate mainly close to shore on short distance routes, often less than 1,000 nautical mile. The transport capacity of the vessels is often less than 15,000 DWT, which is relatively small compared to deep-sea vessels. However, despite its small vessel size, the short-sea sector accounts for more than half of the total tonnage of total maritime transport in Europe [Eurostat, 2022].

Vessel types

The short-sea shipping sector encompasses different types of ships, each with their specific characteristics needed to carry certain cargo. The distribution of ship types is important because different mitigation measures could be feasible for different ship types, due to the ship layout and operational profile.

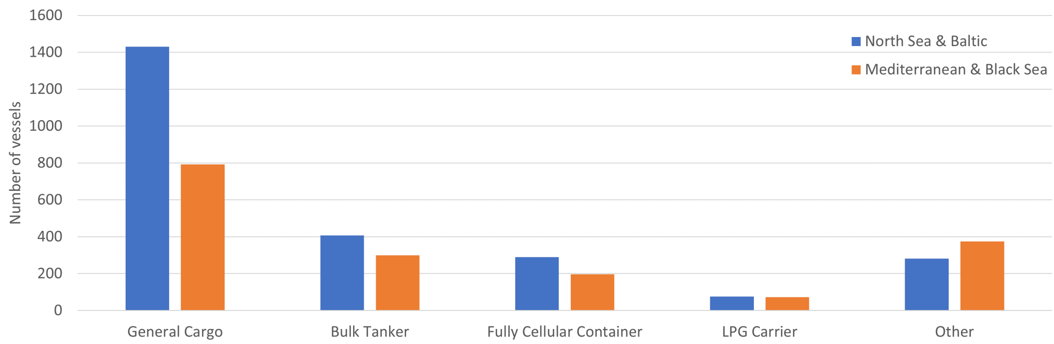


Figure 2.6.: Types of short-sea vessels (below 15,000 DWT) operating in the North-sea & Baltic area and Mediterranean & Black Sea. (Data source: Clarksons [2022])

Figure 2.6 shows the types of short-sea vessels active in Europe, subdivided into the North Sea & Baltic area and Mediterranean and Black Sea. This data is collected from the database of Clarksons [2022], for which several filter where applied which are explained in more detail in Appendix A. Figure 2.6 shows that general cargo is the most common vessel type, accounting for more than 50% of all ships. Other common types are bulk tankers and container ships, which account for more than 15% and 10% of the total number of short-sea ships in Europe.

Age distribution

The age distribution of vessels have various impacts on shipping economics. First of all, it determines the payback period available for retrofitted emission mitigation measures. Secondly, it shows how many ships (transport capacity) will be removed from the market as older ships are being scrapped. Which has a positive impact on the transport rates and vessel value.

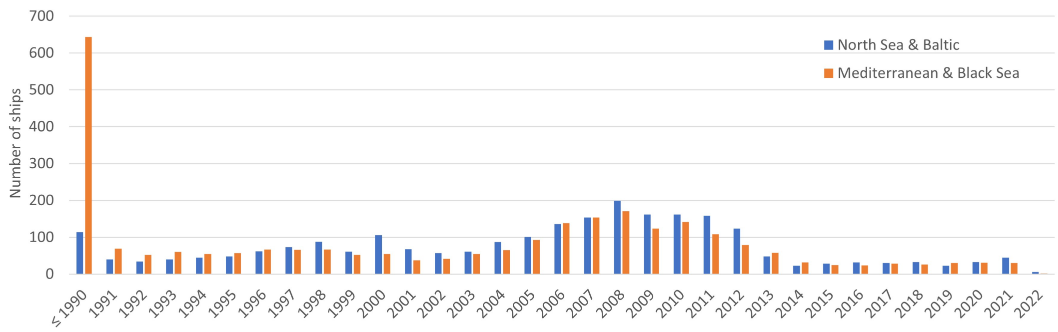


Figure 2.7.: Building year short-sea vessels (below 15,000 DWT) operating in North-sea & Baltic area and the Mediterranean & Black sea area. (Data source: Clarksons [2022])

The short-sea fleet in Europe has average age of 16 years, with most vessels being built between 2005 and 2013 (Fig.2.7). Additionally, Figure 2.7 shows that many vessel operating in the Mediterranean are build before 1990. This spike can be explained by a number of reasons: Western and Northern European shipping companies have age limits, freight companies demand younger, more efficient ships, and loans are harder to get for older ships. However, no scientific research source has been found that explains this phenomena. The owners of older and less efficient vessels face the risk of assets being stranded due to upcoming emission regulations. The owners of these older ships will have to make their ships compliant, sell their ships or scrap their ships.

Voyage distances

The voyage distance distribution of ships determine how much fuel ships need to carry to be able to cover most routes. As already indicated, short-sea vessels operate mainly close to shore on short distance routes. Because few data is publicly available on the number and distances of voyage routes sailed by short-sea vessels in Europe, this report used its own method to collect voyage data. Data of route distances of 3005 voyages to/from the top 35 short-sea ports are collected from the database of Marine Traffic MarineTraffic [2022]. The number of voyages per port are selected relative to the amount of cargo transported per port, based on transport data from from Eurostat Eurostat [2022]. A detailed discussion on the data selection and data filters used can be found in Appendix C.

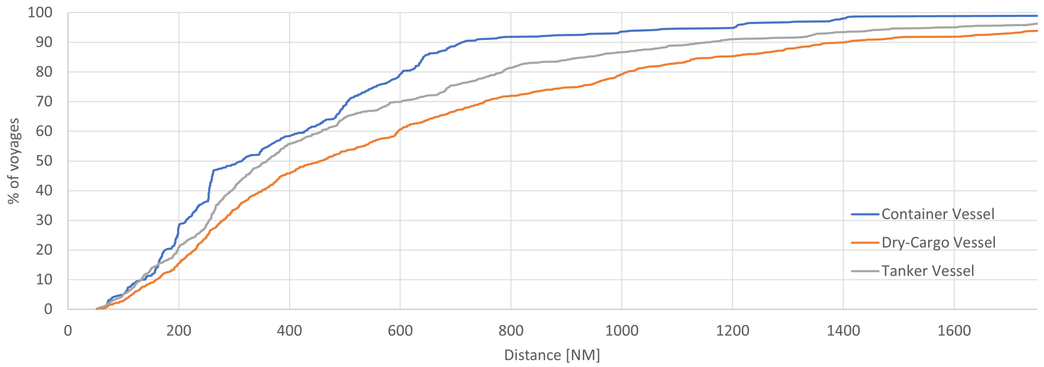


Figure 2.8.: Cumulative distribution of short-sea voyage distances in Europe for container, dry-cargo and tanker vessels below 15,000 DWT. (Data sources: Eurostat [2022], MarineTraffic [2022])

Figure 2.8 shows that there is a significant difference between voyage distances for the top three short-sea vessel types; container, dry-cargo and tankers. This data is also presented for these three vessel types per transport dead-weight capacity in Figures 2.9, 2.10 and 2.11. These figures shows that in general, smaller vessels with lower dead-weight capacity operate on shorter routes.

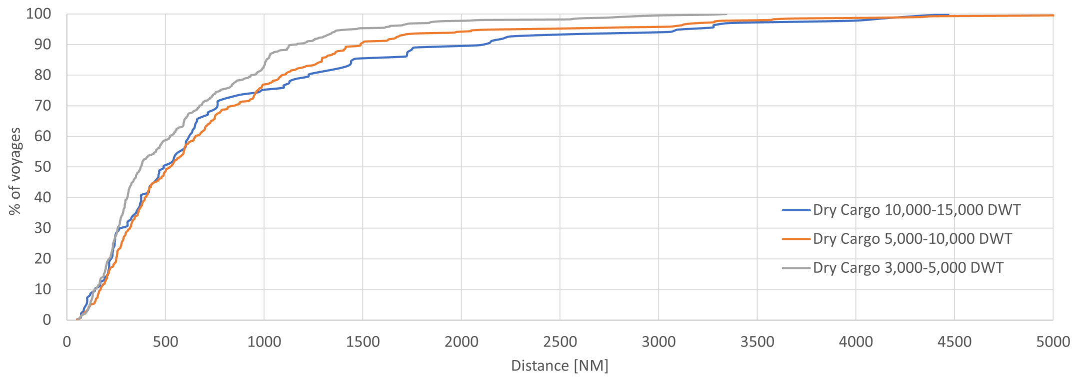


Figure 2.9.: Cumulative distribution of voyage distances of dry-cargo short-sea vessels by capacity. (Data sources: Eurostat [2022], MarineTraffic [2022])

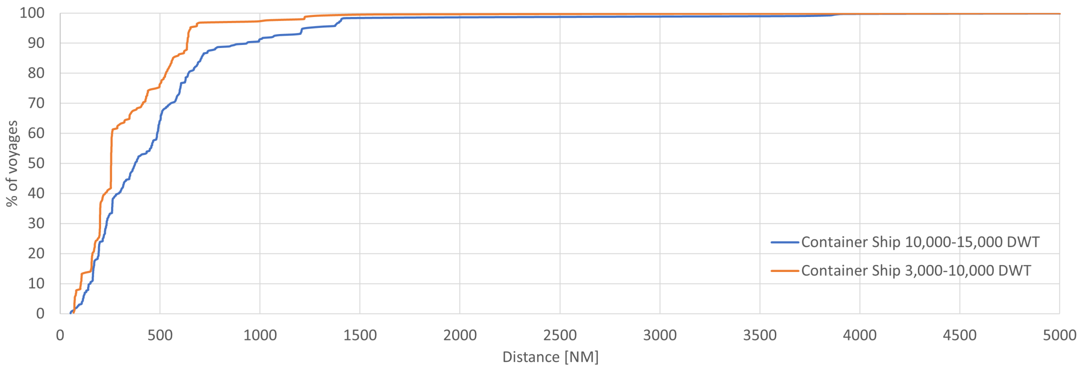


Figure 2.10.: Cumulative distribution of voyage distances of container short-sea vessels by capacity. (Data sources: Eurostat [2022], MarineTraffic [2022])

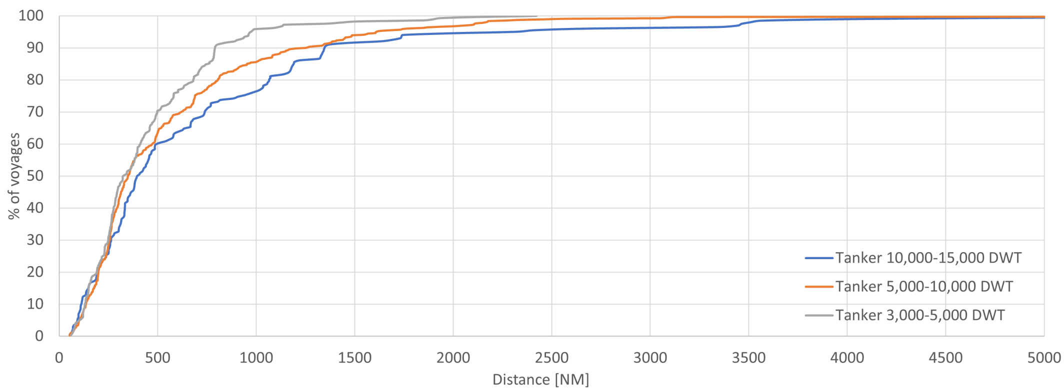


Figure 2.11.: Cumulative distribution of voyage distances of tanker short-sea vessels by capacity. (Data sources: Eurostat [2022], MarineTraffic [2022])

2.2.2. Technical characteristics of representative short-sea vessels

To determine the technical feasibility of the emission mitigation measures discussed in Chapter 2, requirements of measures must be met by the technical and operational characteristics of short-sea vessels. The technical characteristics of five representative vessels are specified.

A set of example vessels are selected based on their representation as percentage of the short-sea fleet in Europe. Based on the vessel type distribution in Figure 2.6, vessels from three vessels types are selected which represent over 75% of the short-sea fleet till 15,000 DWT. Dry-cargo vessels represent 50% of the fleet, and tanker vessels and container vessels 15% and 10% respectively. Three dry-cargo vessels are selected, covering all representative vessel sizes; 3850, 8000 and 14500 DWT. In addition, one 7050 DWT tanker and one 750 TEU/9000 DWT container ship are selected, which represent a medium sized vessel for this vessel type. A benefit of this selection is that an increase of vessel size within a single segment is covered, and multiple vessel types are considered.

Vessel	Deadweight [t]	LOA [m]	Beam [m]	Depth [m]	Draft max [m]	Speed max [kn]
Combi Freighter 3850	3850	90	13	7	5	12
Combi Freighter 8200	8000	120	16	9	7	13.5
Combi Freighter 14000	14500	145	20	11.5	8	15
Product Tanker 8000	7050	105	17	9.5	6.5	12
Container Feeder 800	9300	140	22	9.5	7.5	17

Table 2.1.: Main parameters of example reference vessels. (Data source: Damen [nd])

The main parameters of the representative example vessels are presented in Table 2.1. The values in Table 2.1 are estimates based on vessel dimensions in the portfolio of NESEC and publicly available general arrangements of vessels [Damen, nd].

The following sections discuss the technical characteristics of each vessel type. This provides information on the space and locations available for emission mitigation measures, and determines their technical feasibility.

General Cargo Vessels

General/dry-cargo vessels are the most abundant ship type in the short-sea shipping sector. These vessels often have one deck and have the ability to transport a variety of commodities in different forms such as palletized, boxed, refrigerated and in bulk form. Dry-cargo vessels can roughly be divided into three size categories between 3,000 till 15,000 DWT. Figure 2.1 presents the general dimensions and operating speed for these size categories. General cargo vessels have a simple box-form layout. Space for additional fuel tanks and carbon capture storage are available in the cargo hold, or on top of the hatch covers. The advantage of placing such device in the hull is that it is better protected, and better for ship stability. Placing a device on top of the hatch has the advantage that the cargo space is not reduced. Additionally, general cargo vessels have available space at the bow of the vessel for the placement of wind energy devices. Due to the simple layout of general cargo vessels, the vessel can be retrofitted with an additional midship section.

Tankers

Tankers transport a variety of bulk liquids or gasses in tanks in the hull. There are a variety of tanker designs, all tailored to the type op liquid transported. Crude oil tankers have a double hull to prevent oil leaks and chemical tankers transporting ammonia, toluene, benzene and alcohol products and have special tanks to store the cargo cooled or/and under pressure. On tankers, deck space is available for placement of wind energy devices or alternative fuel tanks. Due to the placement of cargo tanks in the hull, tankers are not suited for retrofitting with an additional midship section.

Container Vessels

Fully Cellular container ships are specially designed to transport containers. The ship is hatch-less and containers are stored one on top of the other. Limited deck space is available as most space is used to stack containers. The stacked containers also limit the airflow, and therefore no space is available to add a wind energy devices. Space for additional fuel tanks or carbon capture devices is available in the cargo hold. Furthermore, due to the simple box-form hull shape of container vessels, the vessel can be retrofitted with an additional midships section.

Conclusion

Available locations and space for additional fuel tanks, wind energy devices and carbon capture devices depend on short-sea vessel types and size. In general, dry-cargo vessel have space to store alternative fuels, add wind energy devices and carbon capture devices. This also applies to tankers, which have extra space on deck for wind energy devices and additional fuel tanks, as this type of ship does not have hatches along the length of the ship. Container vessels have space for fuel tanks and carbon capture devices in the cargo holds. Furthermore, container vessels do not have space for wind energy devices due to the interference of wind and stacked containers. In addition, general cargo and container vessels can increase their cargo capacity by the addition of a midship section, due to their simple box-form hull shape.

3. Concept of the Comparison Tool

This chapter presents a concept methodology for how effect of measures on regulatory compliance and financial viability of measures/strategies to reduce carbon emissions can be compared. First, the requirements for the Comparison Tool are described in section 3.1. From this, the concept of the Comparison Tool is presented in section 3.2.

3.1. Requirements for the comparison model

This section specifies the model requirements needed to fill the knowledge gaps described in section 1.4. The problem solution requirements listed in section 1.2 specify the requirements of the comparison method, which are condensed to the following methodology requirements for the model.

The comparison model must meet the following methodology conditions:

- Apply to (existing) ship types short-sea vessels under 15,000 DWT.
- Include all relevant emission mitigation measures: technical, operational and low-emission fuels.
- Include technically feasible emission mitigation measures, depending on the type and size of the vessel.
- The solution generation methods should be based on a set of ship inputs.
- The solution must provide insight into costs of EU allowance for specific ships.
- The solution must determine the effect of emission mitigation measures on regulatory compliance of specific ships for the CII and EEXI.
- The solution must compare the financial viability of solutions.
- The solution must provide insight into the (price) uncertainties in the approaches used.

3.2. General model description

Several studies provide methods to compare energy mitigating measures. From the literature review in section 1.4.2 and the comparison of the two comparison models most closely related to the problem solution criteria presented in section 1.4.3, suitable comparison methods from other studies are used to fit the methodology requirements of this report.

Solutions are compared for technological feasibility and financial viability. To do this, only technologically feasible mitigation measures are included in the calculation. For a set of ship input values (e.g. ship type, size, fuel consumption etc.), the emission reduction potential and cost of applicable measures are calculated. Using simple low detail calculations, similar to the IMO [nd] comparison model. The CII, EEXI and the cost for EU CO_2 compensation are calculated for the vessel operating in a Business As Usual (BAU) situation. Thereafter, the cost effectiveness and the effect on regulatory compliance of emission-reducing measures can be compared. These steps are illustrated in the general outlines of the model in Figure 3.1.

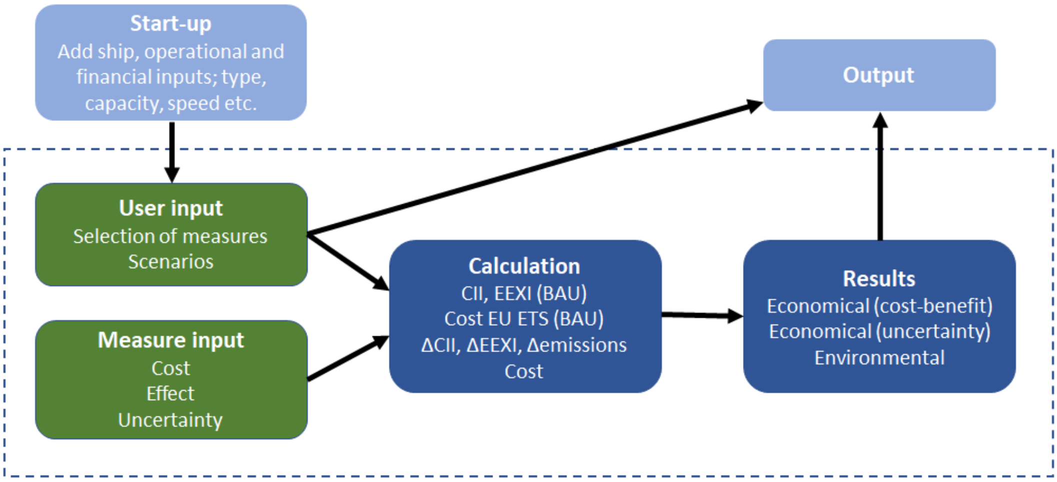


Figure 3.1.: General outline of the Comparison Tool (Source: own source)

4. Design of the Comparison Tool

This chapter discusses the calculation methods used in the Comparison Tool. Figure 4.1 show the components of the Comparison model at a detailed level. Based on a set of ship and financial inputs by the user, the CII, EEXI are calculated. The financial viability of measures are compared by their NPV value of measures. Furthermore, the effect of measures on the CII and EEXI are calculated based on the user inputs and a measure specific inputs. In addition, the fuel tank mass and volume are presented for low-emission fuels. Presenting a first estimate of the impact of alternative fuel strategies on the ship design.

The calculations in the Comparison Tool in Figure 4.1 are split into six blocks. The first two blocks calculate the EEXI and CII and are discussed in sections 4.1 and 4.2. The financial calculations are calculated in the third block and are discussed in section 4.4. Several measures have unique calculation measures and are grouped into 3 blocks, technical measures calculations, low-emission fuels calculations and operational measures calculations. These three blocks are discussed in sections 4.5, 4.6 and 4.7 respectively. Additionally, background information on EU ETS cost calculation methods used in sections 4.5, 4.6 and 4.7 is presented in section 4.3.

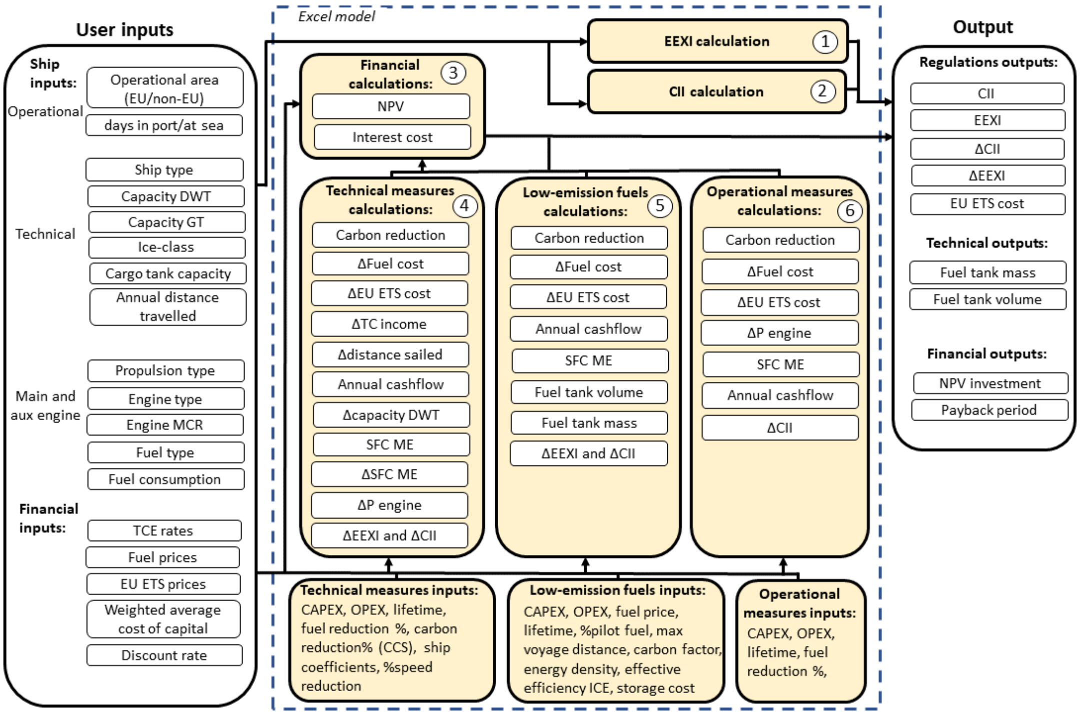


Figure 4.1.: Detailed outline of the Comparison Tool (Source: own source)

Based on the feasibility study in Chapter 2, a selection of measures applicable to short-sea vessels are included in the Comparison Tool. An overview of the included measures is presented in Table 4.1.

Technical measures	Operational measures	Low-emission fuels
• Carbon capture and storage • Increase in capacity (10%, 20% and 30%) • Efficient rudder • Hull coating • Air lubrication • High efficiency propeller • Wake-equalizing duct • Pre and post-swirl devices • Contra rotating propeller • Fixed wings or sails • Engine power limitation (speed reductions: 5%, 10%, 15%, 20%, 25% and 40%)	• Trim and draft optimisation • Weather routing • Just in time arrival	• Methanol • Ethanol • LNG • LPG • Hydrogen • Fully electric (battery powered)

Table 4.1.: Emission reducing measures included in the Comparison Tool

4.1. Calculation of the EEXI

The EEXI calculation is based on the EEDI calculation, but applicable for existing vessels [IMO, 2021a]. The attained EEXI and EEDI are calculated by formula 4.1. The required EEXI depends ship types and size segments [IMO, 2021a].

$$\text{Attained EEXI} = \frac{(\mathrm{P_{ME}} \cdot \mathrm{Cf_{ME}} \cdot \mathrm{SFC_{ME}}) + (\mathrm{P_{AE}} \cdot \mathrm{Cf_{AE}} \cdot \mathrm{SFC_{AE}})}{\mathrm{C} \cdot \mathrm{S}} \tag{4.1}$$

In which:

P_{ME}	Main engine power at 75% MCR	[kW]
Cf_{ME}	Carbon factor of fuel in main engine	[tCO2/t]
SFC_{ME}	Specific fuel consumption at 75% MCR main engine	[g/kWh]
P_{AE}	Auxiliary engine power at 50% MCR	[kW]
Cf_{AE}	Carbon factor of fuel in auxiliary engine	[tCO2/t]
SFC_{AE}	Specific fuel consumption at 50% MCR auxiliary engine	[g/kWh]
C	Transport capacity	[DWT]
S	Speed at 75 % MCR main engine	[kt]

The improvement of the EEXI is based on IMO regulation MEPC.1/Circ. 815 [IMO, 2013]. To improve the EEXI either the engine power, C_f value, SFC must be reduced, or capacity or speed must be increased. The calculation method for the new attained EEXI is specified for each emission mitigation measure in sections 4.5, 4.6 and 4.7. The effect of measures on the EEXI, ΔEEXI, is calculated by equation 4.2.

$$\Delta\text{EEXI} = \text{Attained EEXI} - \text{New Attained EEXI} \tag{4.2}$$

4.2. Calculation of the CII

The CII is calculated using formula 4.3. The input for transport capacity is in DWT, except for cruise passengers ships, ro-ro cargo and passenger ships where gross tonnage is used.

$$\text{Attained CII} = \frac{(\text{FC}_{ME} \cdot Cf_{ME}) + (\text{FC}_{AE} \cdot Cf_{AE})}{\text{C} \cdot D} \tag{4.3}$$

In which:

FC_{ME}	Fuel consumption main engine per annum	[t/yr.]
Cf_{ME}	Carbon factor of fuel main engine	[tCO2/t]
FC_{AE}	Fuel consumption auxiliary engine per annum	[t/yr.]
Cf_{AE}	Carbon factor of fuel auxiliary engine	[tCO2/t]
C	Transport capacity	[DWT/GT]
D	Total distance sailed per annum	[nm]

To improve the CII either the fuel consumption or the C_f value must be reduced, or capacity or distance sailed must be increased. The calculation method for the new attained CII is specified for each emission mitigation measure in sections 4.5, 4.6 and 4.7. The effect of measures on the CII, ΔCII, is calculated by equation 4.4.

$$\Delta\text{CII} = \text{Attained CII} - \text{New Attained CII} \tag{4.4}$$

4.3. EU ETS cost calculation

Emission allowances must be bought to cover the tonnages CO_2 emitted for vessel of 5000 GT and above sailing in the European Area [EC, 2003]. This applies to 100% of emissions for voyages between EU ports and 50% of emissions from an EU port to an non-EU port and vice versa [KVNR, 2022b]. The regulations have a two year initial phase-in period in which only a part of the emissions are covered, reaching 100% after three years. In 2025, 2026 and 2027, the verified emissions must be surrendered for consecutive 40%, 70% and 100% [KVNR, 2022b]. The allowances are an expense that can be lowered by reducing CO_2 emissions. Hence, the reduction in emission allowance cost are presented as a positive cash-flow in the cash-flow calculations of carbon reducing measures. In addition, as the amount of coverage depends on the operational area of the vessel, the Comparison Tool calculates emission costs (and cost reductions of measures) based on operational inputs; % voyages between non-EU ports, % voyages between EU and non-EU ports, and % voyages between non-EU ports. The formulas for EU ETS cost calculations are specified per emission mitigation measure in sections 4.5, 4.6 and 4.7.

4.4. Financial equations applicable to all measures

This section discusses financial calculation methods that apply to all emission reduction measures. These methods are indicated as block number three in the Comparison Tool structure overview (Fig.4.1).

The measures are compared on their financial viability as a Net Present Value (NPV) calculation of the investment in a single measure. The NPV is only calculated in relation to the investment in the emission mitigation measure and is completely separate from an investment in a ship. NPV is chosen as comparison parameter as it provides a non-biased comparison and gives a clear indication if an investment in a measure is profit-making or loss-making. The formula for the NPV calculation is presented in equation 4.5. In which a discount rate of 4% is used, based on the historical average rate in the EU area [TE, 2023a].

$$NPV_m = \sum_{LT} \frac{CF_m}{(1+r)^{LT}} \tag{4.5}$$

In which:

NPV_m	Nett present value of investment in a measure	[EUR]
CF_m	Annual cash flow of measure	[EUR/yr]
r	Discount rate	[-]
LT	Lifetime of asset	[yr]

In general, the cash flows in the NPV calculation represent costs related to the implementation of single measures (negative cash flows) and cost reduction or additional income related to the implementation of measures (positive cash flows). The type of costs and cost reduction in the cash flow analysis varies per measures. To illustrate the cash flow analysis in the Comparison Tool, an example analysis for a pre and post-swirl device on dry cargo vessel with transport capacity range 3,000-5,000 DWT is presented in Appendix F.

The financial costs in the cash flow calculations consist of the annual repayments of the investment (equation 4.7) and the annual financing cost (equation 4.9). The investment is repaid on a straight-line basis to compare measures equally. The annual financing cost are based on the assets value in a specific year (equation 4.8). The financing cost for all measures are calculated by averaging the rate off the companies sources of capital. This method was chosen as it calculates the financing costs equally for all measures, instead of calculating the financing costs on a loan basis. A loan-based finance structure is not suitable as loan finance is not available to all measures because the collateral cannot be separated from the ship itself or loan values are to low to be viable [NESEC, 2023]. The Weighted Average Cost of Capital (WACC) is determined using equation 4.6, in which the investment consist of three sources of capital; 60% senior (bank) loan, 20% junior loan and 20% equity with a consecutive rate of 5%, 8% and 12% [NESEC, 2023]. This results in a WACC of 7%.

$$\text{WACC} = \sum SC_i \cdot r_i \tag{4.6}$$

In which:

WACC	Weighted Average Cost of Capital	[-]
SC_i	Source of capital	[-]
r_i	Cost rate of capital	[-]

$$AR_m = I/LT \tag{4.7}$$

In which:

AR_m	Annual repayment of investment in measure	[EUR/yr]
I	Initial asset value	[EUR]

$$AV_m = I - \sum_{0}^{i} AR_m \tag{4.8}$$

In which:

AV_m	Asset value in specific year i	[EUR]

$$C_{im} = \text{WACC} \cdot AV_m \tag{4.9}$$

In which:

C_{im}	Annual financing cost of measure in a specific year	[EUR]

4.5. Technical measures

4.5.1. Fuel-saving technologies

Various technical fuel-saving measures are included in the Comparison Tool. These consist of: efficient rudder, hull coating, air lubrication, high-efficiency propeller, wake-equalizing duct, pre and post-swirl devices, contra rotating propeller, fixed wings and sails. The method of implementation of these fuel saving measures are based on methods by the Appraisal Tool [IMO, nd]. This method calculates the effect of fuel saving measures based on the average fuel reduction, installation cost, and OPEX per vessel type and size. Although the Appraisal Tool has documented the estimated input values per fuel saving measure, documentation on the equations used is lacking. Therefore this research used its own equations.

First, the mass CO_2 increase or reduction is calculated based on the average annual fuel reduction percentage of measures in equation 4.10. The fuel-saving measures listed only affect the fuel consumption of the main engine and therefore CO_2 mass reduction is calculated based on the annual mass fuel consumed by the main engine.

$$\Delta m_{CO2m} = C_{fME} \cdot m_{TAFC} \cdot C_{FR\%m} \tag{4.10}$$

In which:

Δm_{CO2m}	Change of mass CO2 emitted	[tCO2]
C_{fME}	Fuel carbon factor	[tCO2/t]
m_{TAFC}	Total mass annual fuel consumption main engine	[t]
$C_{FR\%m}$	Average annual fuel reduction percentage of measure	[-]

Thereafter, fuel cost increase or reduction is calculated by equation 4.11. The EU ETS cost reduction depend on the CO_2 mass reduction and the operational are inputs of the vessel, its calculation is presented in equation 4.12. Based on these costs, and the financial costs described in section 4.4, the annual cash flow per measure is calculated by equation 4.13.

$$\Delta C_{\text{fuel}m} = C_{RF\%m} \cdot P_{\text{fuel}} \cdot m_{TAFC} \tag{4.11}$$

In which:

$\Delta C_{\text{fuel}m}$	Change in fuel cost	[EUR]
P_{fuel}	Fuel price	[EUR/t]

$$\Delta C_{EUETSm} = (P_{EUETS} \cdot \Delta m_{CO2m})(V_{EU} + 0.5V_{EU,nonEU}) \tag{4.12}$$

In which:

ΔC_{EUETSm}	Change in EU ETS cost	[EUR]
$P_{EU\ ETS}$	EU ETS allowance price	[EUR/tCO2]
V_{EU}	Percentage voyages between EU ports	[-]
$V_{EU,nonEU}$	Percentage voyages between EU and non EU ports	[-]

$$CF_{\text{m}} = \Delta C_{\text{fuel}\ m} + \Delta C_{EUETSm} - AR_m - C_{im} - OPEX_m \tag{4.13}$$

In which:

CF_{m}	Annual cash flow of measure	[EUR/yr]
$OPEX_m$	OPEX of measure	[EUR/yr]

The input values for equations 4.10, 4.11, 4.12, 4.13 are specified per measure in Appendix D, including all references to literature and data sources.

The effect of fuel-saving measures on the calculation for EEXI is specified in equation 4.14. This method is based on IMO regulation MEPC.1/Circ.815, on the implementation of energy saving measures on ships [IMO, 2013]. The EEXI is reduced by a correction on the main engine power input, which is calculated in equation 4.15.

$$\text{New Attained EEXI} = \frac{((P_{ME} - \Delta P_{ME}) \cdot Cf_{ME} \cdot SFC_{ME}) + (P_{AE} \cdot Cf_{AE} \cdot SFC_{AE})}{C \cdot S} \tag{4.14}$$

In which:

ΔP_{ME}	Power reduction main engine	[kW]

$$\Delta P_{ME} = P_{ME,75\%} \cdot C_{FR\%m} \tag{4.15}$$

In which:

ΔP_{ME}	Power reduction main engine	[kW]
$P_{ME,75\%}$	Power main engine at 75% MCR	[kW]

The effect of fuel-saving measures on the calculation for CII is presented in equation 4.16. In which the CII is reduced due to a reduction in CO_2 mass emitted.

$$\text{New Attained } CII = \frac{(FC_{ME} \cdot Cf_{ME}) + (FC_{AE} \cdot Cf_{AE}) - \Delta m_{CO2m}}{C \cdot D} \tag{4.16}$$

4.5.2. Carbon capture and storage device

The CO_2 mass reduction of carbon capture and storage systems are calculated in this report based on an input for the carbon percentage captured, presented in equation 4.17. In reality however, the device may also increase fuel consumption when high percentages CO_2 are captured. This effect is caused by multiple factors; an increase in ship weight by the stored carbon, an increase in fuel consumption due to energy demands from the device, and effects (back-pressure) of the device on the flow of exhaust gasses. This report does not have access to data of these effects, partly due to the relatively young age of this technology. Therefore carbon capture and storage is included in the Comparison Tool with the rough assumptions that 25% of CO_2 emission are captured and the effects of the system on fuel consumption are neglected.

$$\Delta m_{CO2m} = C_f \cdot m_{TAFC} \cdot CR_m \tag{4.17}$$

In which:

Δm_{CO2m}	Change in mass CO2 emitted	[tCO2]
C_f	Fuel carbon factor	[tCO2/t]
m_{TAFC}	Annual fuel consumption aux. and main engine	[t]
CR_m	Carbon capture percentage of measure	[-]

As carbon capture and storage devices reduces both carbon and sulphur emissions [ValueMaritime, ndb], the fuel cost reduction is calculated based on the price spread between ULSFO and HFO. Since ULSFO (with 0.1% fuel sulphur content) is required for conventional vessel sailing in emission control areas, and HFO (with high sulphur contents) can be used for vessel equipped with a sulfur filter system. This assumption implies that the financial viability of carbon capture and storage systems are highly dependent on the price assumptions of HFO and MGO or ULSFO. The fuel cost reduction calculation is presented in equation 4.18. In this calculation fuel mass consumed is corrected for the difference in energy density difference between USLFO and HFO, assuming an unchanging main engine SFC.

The EU ETS cost reduction is calculated using the same method as fuel-reducing technologies, presented in equations 4.12. Furthermore, the cash flow calculation method presented in the equation 4.13 is used.

$$\Delta C_{\text{fuel } m} = m_{TAFC} \cdot (U_{ULSFO}/U_{HFO}) \cdot (P_{\text{fuel ULSFO}} - P_{\text{fuel HFO}}) \tag{4.18}$$

In which:

ΔC_{fuelm}	Change in fuel cost	[EUR]
$P_{\text{fuel ULSFO}}$	Fuel price ULSFO	[EUR/t]
$P_{\text{fuel HFO}}$	Fuel price HFO	[EUR/t]
U_{ULSFO}	Energy density ULSFO	[GJ/t]
U_{HFO}	Energy density HFO	[GJ/t]

The input values for equations 4.12, 4.13, 4.17 and 4.18 are specified for carbon capture and storage systems per vessel type and size in Appendix D, including all references to literature and data sources.

The value of the percentage carbon captured is directly related to the new values for the EEXI and CII. The adjusted EEXI is calculated by equation 4.19. The adjusted CII is calculated based on the reduction CO_2 mass, using the same method as equation 4.16.

$$\text{New Attained EEXI} = \frac{(P_{ME} \cdot Cf_{ME} \cdot SFC_{ME})\,(1 - CR_m) + (P_{AE} \cdot Cf_{AE} \cdot SFC_{AE})}{C \cdot S} \tag{4.19}$$

4.5.3. Capacity increase

Increasing a ships capacity by retrofitting vessels with an additional midship section is a method shipowners can use to circumvents the EEXI and CII regulations. It does not reduce carbon emissions, but aims to increase transport efficiency. In practice an increase in capacity (due to an increase of the length of the vessel) may be constraint by port dimensions. The effects of an increase of 10%, 20% and 30% dead-weight tonnage on EEXI and CII are included in the Comparison Tool. Increasing capacity by adding a midship-section has effect on the ship's resistance, and therefore its operation speed. Furthermore, the change in speed and capacity affects the earning capabilities of the vessel.

First, the new ship speed is estimated by using the Holtrop-Mennen resistance estimation method [Holtrop, 1982]. The speed reduction is estimated for a constant (hull) resistance, therefore the engine power does not change from the original vessel. Only two input parameters change in this estimation method when capacity is increased; the waterline length and the hull wetted area. The hull wetted area of the vessel is estimated based on Holtrop [1982], using formula 4.20.

$$S_{wa} = L_{wl}(2T + B)\sqrt{C_m}\left(0.453 + 0.4425C_b - 0.2826C_m - 0.003467\left(\frac{B}{T}\right) + 0.3696C_{wp}\right) \tag{4.20}$$

In which:

S_{wa}	Hull wetted area	[m2]
L_{wl}	Waterline length	[m]
C_m	Mid-ship block coefficient	[-]
C_{wp}	Water plane area coefficient	[-]
C_b	Block coefficient	[-]
B	Beam of the vessel	[m]
T	Draft of the vessel	[m]

The length of the additional midship section is estimated by formula 4.21, based on the relation between increase in DWT and the area of the midship section. This estimate neglects the weight of the steel structure itself, but provides a good first approximation.

$$L_{\text{ms}} = \frac{C \cdot (1 + \Delta Cap_{dwt})}{C_m \cdot B \cdot T \cdot \rho_w} \tag{4.21}$$

In which:

L_{ms}	Length additional midship section	[m]
ρ_w	Density of seawater	[t/m3]

The values for C_{wp} and C_m are approximated by formulating their relation to C_b. C_{wp} is estimated using the 'Normal selection' method described by Papanikolaou [2014], and is presented in equation 4.22. C_m is estimated using the 'Laboratory HSVA' method described by Papanikolaou [2014], and is presented in equation 4.23. Furthermore, the change in the value of hull coefficients due to an increase in transport capacity is neglected. This is chosen as the effect of increase in capacity on these values are negligible.

$$C_{wp} = \frac{1 + 2C_b}{3} \tag{4.22}$$

$$C_M = \frac{1}{1 + (1 - C_B)^{3.5}} \tag{4.23}$$

Using equations 4.20, 4.21 4.22 and 4.23, the adjusted hull wetted area and waterline length are calculated by equations 4.24 and 4.25 respectively. These adjusted values are used to estimate the speed reduction at a constant (hull) resistance using Holtrop [1982].

$$\text{Adjusted } L_{\text{wl}} = L_{\text{ms}} + L_{\text{wl}} \tag{4.24}$$

$$\text{Adjusted } S_{\text{wa}} = (L_{Lwl} + L_{\text{ms}})(2T + B)\sqrt{C_m}\left(0.453 + 0.4425C_b - 0.2826C_m - 0.003467\left(\frac{B}{T}\right) + 0.3696C_{wp}\right) \tag{4.25}$$

The effect of capacity increase on the income and operation of the vessel is calculated as follows. Due to a possible speed reduction, the number of days with TCE income decrease, which is calculated in equation 4.26. This calculation is based on the vessel operational profile, number of days at sea and number of days in port. A speed reduction results in a reduction of income, which is calculated in equation 4.27. This equations takes the increase of income into account due to the increased capacity. The increase is capacity is however not proportional to the increase in income, as freight rates per tonne cargo diminish when ship capacity increase. To account for this, the increase in income is estimated to be 70% of the time charter rate per ton per day and is presented in equation 4.27 as a correction factor.

$$\Delta D_{TCE} = \left(1 - 365/\left((D_{s0}/\left(1 - SR_{\%}\right)\right) + D_{p0}\right) \cdot 365 \tag{4.26}$$

In which:

ΔD_{TCE}	Change of number of days with TCE income	[days]
D_{s0}	Days at sea before speed reduction	[days]
D_{p0}	Days in port before speed reduction	[days]
$SR_{\%}$	Percentage speed reduction	[-]

$$\Delta IC_m = \Delta D_{TCE} \cdot TCE_{\text{rate}} + (D_{s0} - \Delta D_{TCE}) \cdot (\Delta Cap_{dwt} \cdot C_c \cdot TCE_{\text{rate}}) \tag{4.27}$$

In which:

ΔIC_m	Change in income of vessel	[EUR]
TCE_{rate}	Time charter equivalent	[EUR/day]
ΔCap_{dwt}	Percentage dwt capacity increase	[-]
C_c	Correction factor	[-]

Based on the change of income, and the financial costs described in section 4.4, the annual cash flows of measures are calculated by equation 4.28.

$$CF_{\mathrm{m}} = \Delta IC_m - AR_m - C_{im} - OPEX_m \tag{4.28}$$

The input values for equation 4.28 are specified for capacity increase per vessel type and size in Appendix D, including all references to literature and data sources.

The effect of capacity increase on the calculation for the EEXI is straightforward and is presented in equation 4.29.

$$\text{New Attained EEXI} = \frac{(P_{ME} \cdot Cf_{ME} \cdot SFC_{ME}) + (P_{AE} \cdot Cf_{AE} \cdot SFC_{aux})}{(C + \Delta CAP_{AE}) \cdot S} \tag{4.29}$$

The effect of capacity expansion on the calculation for the CII is less straightforward, as distance sailed per year reduces due to speed reduction. The adjusted CII is calculated by equation 4.30. The new annual distance sailed is calculated by equation 4.31. This calculation is based on the number of days sailing and number of days in port after speed reduction, which are calculated in equations 4.33 and 4.32.

It is assumed that the annual fuel consumption of the main engine remains the same when capacity is increased, as the ship's resistance remains constant. Please note that the reduction in fuel consumption due to the change in days sailing, and days in port, is not taken into account and can be included into an improved version of the Comparison Tool. As fuel consumption in port is lower than fuel reduction while sailing, the value for CII would improve when this effect is taken into account. As speed reduction for the reference vessels in the case study (Figure 5.1) is limited, the effects of this assumption have no significant impact on the results in this report.

$$\text{New Attained } CII = \frac{(FC_{ME} \cdot Cf_{ME}) + (FC_{AE} \cdot Cf_{AE})}{C \cdot d_1} \tag{4.30}$$

In which:

d_1	Annual distance sailed after speed reduction	[nm]

$$d_1 = (D/\,(D_{s0})) \cdot (1 - SR_{\%}) \cdot D_{s1} \tag{4.31}$$

In which:

d_1	Annual distance sailed after speed reduction	[nm]
D	Annual distance sailed before speed reduction	[nm]

$$D_{p1} = \left(D_{p0} \cdot 365\right) / \left(D_{s0} / \left(1 - SR_{\%}\right) + D_{p0}\right) \tag{4.32}$$

In which:
D_{p1} Days in port after speed reduction [days]

$$D_{s1} = 365 - D_{p1} \tag{4.33}$$

In which:
D_{s1} Days sailing after speed reduction [days]

4.5.4. Slow steaming (engine de-rating)

Slow steaming, or the de-rating of the main engine, offers the possibility to fuel consumption and carbon emissions. This measure is considered a technical measure because the technical arrangement of the ship's engine is changed (semi)permanently. Slow steaming causes a shift on the power-speed curve. This rapport estimates the 'new' power based on the cubic relation of engine power and ship speed [Hans Klein Woud, 2002]. Research on slow-steaming by Lindstad et al. [2011] and CEDelft [2011] uses the same method, which yields a good first estimate. The Comparison Tool calculates the effects of slow steaming for a wide range of speed reduction, 5%, 10%, 15%, 20%, 25% and 40%, which offers the ability to determine an optimal speed reduction percentage.

Slow steaming affects ship profitability in a number of ways, and depends on the values for time charter rates, fuel-prices, cost of engine modifications and the cost of EU ETS allowances. The cost reduction for fuel savings is included as positive cash flows in the Comparison Tool, and is calculated in equation 4.34. The loss of transport capability due to lower speeds is included in the Comparison Tool as a negative cash flow, and is calculated in equation 4.35. This opportunity cost is calculated based on the decrease in 'days sailing' and the time charter rate per day. The reduction in days with income is calculated by equation 4.36, based on the ships operational inputs number of days sailing and days in port. The annual distance travelled, number of days in port and number of days sailing after speed reduction are calculated using equations 4.31, 4.32 and 4.33. These are the same equations used to include the effect of speed reduction on the ship's operational profile for capacity increase.

Interestingly, a lower speed results in time increase per voyage but loading/offloading time stays constant. Therefore, speed reduction percentage is not equal to the percentage time increase for one trip (loading of cargo + sailing + offloading of cargo). This shows that the fuel-reduction potential of slow steaming highly depend on the the operational profile of the vessel. Logically, this means that ships with on average more days per year in port benefit less from the fuel reduction due to slow steaming.

The cost reduction of EU ETS cost are calculated in equation 4.37. This calculation is based on mass CO_2 reduced, which is calculated by equation 4.38. Based on the changed fuel and EU ETS cost, and the financial costs described in section 4.4, the annual cash flow per measure is calculated by equation 4.39. The system cost in this cash flow calculation are specified in Appendix D.

$$\Delta C_{\text{fuel } m} = \left(1 - (1 - SR_{\%})^3\right) \cdot P_{\text{fuel}} \cdot m_{TAFC} \tag{4.34}$$

In which:

$\Delta C_{\text{fuel } m}$	Change in fuel cost	[EUR]
P_{fuel}	Fuel price	[EUR/t]
$SR_{\%}$	Percentage speed reduction	[-]
m_{TAFC}	Total mass annual fuel consumption main engine	[t]

$$\Delta IC_m = \Delta D_{TCE} \cdot TCE_{\text{rate}} \tag{4.35}$$

In which:

ΔIC_m	Change of income of vessel	[EUR]
TCE_{rate}	Time charter equivalent	[EUR/day]
ΔD_{TCE}	Change of number of days with TCE income	[days]

$$\Delta D_{TCE} = \left(1 - 365/\left((D_{s0}/\left(1 - SR_{\%}\right)) + D_{p0}\right) \cdot 365 \tag{4.36}$$

In which:

ΔD_{TCE}	Change of number of days with TCE income	[days]
D_{s0}	Days at sea before speed reduction	[days]
D_{p0}	Days in port before speed reduction	[days]

$$\Delta C_{EUETSm} = (P_{EUETS} \cdot \Delta m_{CO2m})(V_{EU} + 0.5V_{EU,nonEU}) \tag{4.37}$$

In which:

ΔC_{EUETSm}	Change of EU ETS cost	[EUR]
$P_{EU\ ETS}$	EU ETS Allowance price	[EUR/tCO2]
V_{EU}	Percentage voyages between EU ports	[-]
$V_{EU,nonEU}$	Percentage voyages between EU and non EU ports	[-]

$$\Delta m_{CO2m} = C_f \cdot m_{TAFC} \cdot \left(1 - (1 - SR_{\%})^3\right) \tag{4.38}$$

In which:

Δm_{CO2m}	Change of mass CO2 emitted	[tCO2]
C_f	Fuel carbon factor	[tCO2/t]

$$CF_{\text{m}} = \Delta C_{\text{fuel } m} + \Delta C_{EUETSm} - \Delta IC_m - AR_m - C_{im} - OPEX_m \tag{4.39}$$

In which:

CF_{m}	Annual cash flow of measure	[EUR/yr]

The effect of slow steaming on the EEXI depends on the amount of speed reduction and the corresponding power reduction of the main engine. In addition, the SFC changes due to the new operating point of the engine. The calculation method for the EEXI after engine power limitation is presented in equation 4.41.

The main engine power after speed reduction is calculated by equation 4.40, based on the cubic relation between ship speed and required power. Furthermore, regulations by IMO [2013] prescribe that power input for EEXI changes when the engine is derated, from engine power at 75% MCR to engine power at 83% MCR. This implies that there is a threshold of % speed reduction before a lower EEXI value can be obtained from slow-steaming.

The SFC at the new operational point of the engine is calculated based on the SFC-Power graphs in Figure 4.2. The value for the new SFC depends on the MCR of the main engine after engine power limitation, and the engine type, which is an input in the Comparison Tool. Details on the engine types in Figure 4.2 are presented in Table 4.2.

$$P_{MCR1} = P_{MCR0} \cdot (1 - SR_{\%})^3 \tag{4.40}$$

In which:

P_{MCR1}	Max MCR main engine after engine power limitation	[kW]
P_{MCR0}	Max MCR main engine before engine power limitation	[kW]

$$\text{New Attained EEXI} = \frac{(0.83 \cdot P_{MCR1} \cdot Cf_{ME} \cdot SFC_{ME1}) + (P_{AE} \cdot Cf_{AE} \cdot SFC_{AE})}{C \cdot (S\,(1 - SR_{\%}))} \tag{4.41}$$

In which:

P_{MCR1}	Max MCR main engine after power limitation	[kW]
SFC_{ME1}	SFC at 83% MCR main engine, adjusted for ME power limitation	[g/kWh]
$SR_{\%}$	Percentage speed reduction	[-]

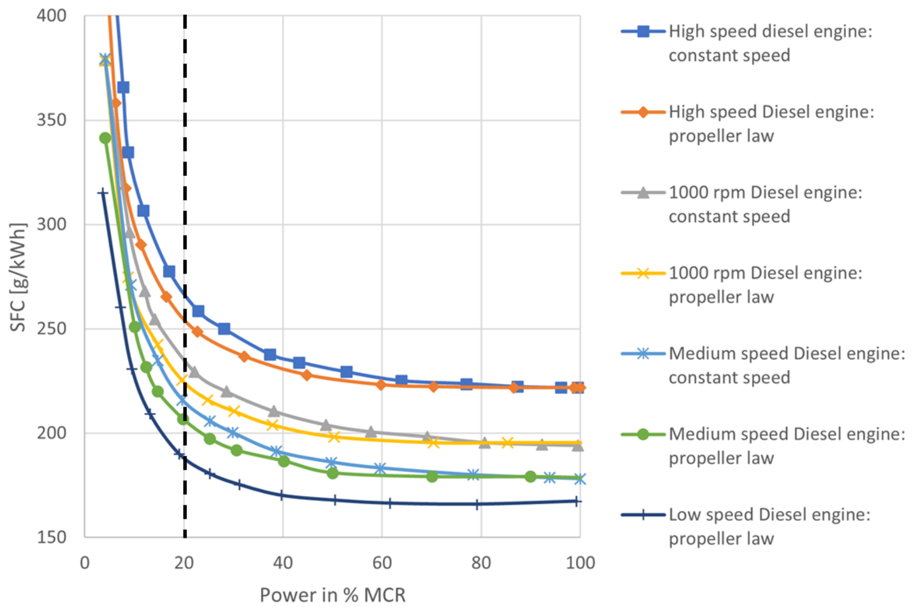


Figure 4.2.: Specific fuel consumption for propeller load (propeller law) and for generator load (constant speed).(Source: [Hans Klein Woud, 2002])

Specific data	Low-speed DE	Medium-speed DE	High-speed DE
Process	2-stroke	4-stroke	4-stroke
Output range [kW]	8,000-80,000	500-35,000	500-9,000
Output speed range [rpm]	80-300	300-1,000	1,000-3,500
Fuel type	HFO	HFO/MDO	MDO
SFC [g/kWh]	160-180	170-210	200-220

Table 4.2.: Performance parameters of Diesel Engines (DE). (Source: [Hans Klein Woud, 2002])

The effect of slow steaming on the CII is due to a reduction in both fuel consumption and distance travelled, and is calculated by equation 4.42. The new annual distance travelled (d_1) is calculated by equation 4.31, making uses of the same methods of calculation of the number of days in port and days sailing in equations 4.32 and 4.33.

$$\text{New Attained CII} = \frac{(FC_{ME} \cdot Cf_{ME}) + (FC_{AE} \cdot Cf_{AE}) - \Delta m_{CO2m}}{C \cdot d_1} \tag{4.42}$$

4.6. Operational measures

Three operational measures are included in the Comparison Tool; trim and draft optimization, weather routing and just in time arrival. These measures are included in the Comparison Tool using the same methods as fuel-saving technologies, in section 4.5.1. In which the input for average fuel reduction percentage determine the CO_2 reduction potential and EU ETS and fuel cost reduction.

The operational measures have no effect on the EEXI, as this is inherent in its calculation method. The effect of operational measures on the CII is due to its reduction of fuel consumption, similarly to the CII calculation for fuel reducing measures in equation 4.16. The systems cost and fuel reduction potentials are specified in Appendix D.

4.7. Low-emission fuel

Several alternative fuels are included in the Comparison Tool; methanol, ethanol, LNG, LPG, hydrogen and fully electric (battery powered). In this report the carbon reduction potential for each fuel is considered from a tank-to-propeller perspective, as the IMO emission regulations are also based on this [MEPC72, 2018] [IMO, 2021a]. The cost of alternative fuel strategies depend on multiple factors; the amount of fuel stored space required, fuel price, CO_2 content per energy output, cost of engine (modification) and cost of fuel storage systems.

First, the total annual fuel consumption for an alternative fuel is determined based on the ship's input 'yearly fuel mass consumed' by equation 4.43. It is assumed that the base case vessel uses ULSFO, as this fuel type is required for conventional vessel sailing in ECAs. Based on the annual fuel mass consumed, and the SFC of the engine, the fuel's energy content is quantified is equation 4.44. The calculation method in equation 4.44 requires inputs for SFCs of alternative fuels. These are, however, not yet known in literature for IC engines fueled by methanol or hydrogen due to a lack of data from ships using these fuels. Therefore, this study estimates the SCFs of fuel alternatives based on its energy density and the effective efficiency of IC used, as presented in equation 4.45.

This report only covers IC engine in its scope, as this provides a first estimate of the impact of low-emission fuels on the ship design. The values for the effective efficiencies and percentage pilot fuel for each low-emission fuel are estimated based on literature. Furthermore, the engines conversion cost, cost for fuel storage and other fuel specific assumptions are specified. An overview of all key fuel parameters used in the Comparison Tool are presented in Table 4.3. A full overview of all fuel inputs is included in Appendix E, including all references to data sources.

$$m_{TAFC1} = \left(E_f\,(1 - PF_{\%}) \cdot SFC\right) / \left(10^6\right) \tag{4.43}$$

In which:

m_{TAFC1}	Annual fuel consumption main engine of alternative fuel	[t]
$PF_{\%}$	Percentage diesel pilot fuel required	[-]
SFC	Specific fuel consumption of specific fuel	[g/kWh]
E_f	Energy in fuel	[kWh]

$$E_f = \left(m_{TAFC_0}/SFC\right) \cdot 10^6 \tag{4.44}$$

In which:

E_f	Energy in fuel	[kWh]
m_{TAFC_0}	Annual fuel consumption main engine of input vessel	[t]

$$SFC = 3600/\left(U_f \cdot \eta_e\right) \tag{4.45}$$

In which:

SFC	Specific fuel consumption of specific fuel	[g/kWh]
U_f	Energy density of specific fuel	[GJ/t]
η_e	Effective efficiency engine for specific fuel	[-]

Fuel type	**% pilot fuel**	η_e **ICE**	**Average SFC [g/kWh]**	**Energy density [GJ/t]**	**Energy density [GJ/m3]**	**Cf [tCO2/tfuel]**	**Price [€/t]**
ULSFO	0	0.43	195	43.0	35.7	3.20	700
LPG (butane)	3	0.43	171	49.1	26.7	3.03	496
LNG	2	0.43	156	53.6	21.2	2.75	712
Methanol	5	0.43	425	19.7	14.9	1.37	321
Ethanol	15	0.31	415	28.0	21.0	1.91	796
Hydrogen	0	0.25	120	120.0	8.5	0.00	2020
Fully electric*	0	0.95*	n/a	0.25 [kWh/kg]*	700 [kWh/m3]*	0	0.091 [€/kWh]

Table 4.3.: Overview of the key parameters for the marine fuels and energy converters used in the Comparison Tool (*battery powered)

Cost for storage systems and space and weight requirements for fuel storage systems depend on the minimal amount of fuel required. This report quantifies the minimal size and weight of alternative fuels storage systems based on the voyage distance distribution of short-sea vessels. The minimal energy storage is determined so that at least 90% of all voyages distances are covered for the five short-sea reference vessels. This method provides a good first basis for comparing alternative fuels with other emission reduction measures. The limit of 90% is chosen because this ensures that most voyages can be made with a full fuel tank. Without having an unnecessarily large amount of fuel storage capacity installed, which results in high investment costs and technical challenges.

The maximal distances are established based on the cumulative distribution of voyage distances of the reference vessels in Figures 2.9, 2.10 and 2.11. This results in maximal voyage distances of 1200, 1500 and 2000 nautical miles for the dry-cargo reference vessel of capacity ranges 3.000-5.000, 5.000-10.000 and 10.000-15.000 DWT. For the short-sea tanker and container reference vessels, the maximal distances are 1.500 and 1.000 nautical mile respectively. Using these values, the minimal volume of the fuel tank is calculated by equation 4.46. This calculation is based on the total volume of alternative fuel used annually, which is calculated in equation 4.47 based on the volumetric energy density of the alternative fuel. The minimal mass of the fuel tank is calculated by similar means in equation 4.48. Energy density inputs in these equations are listed in Table 4.3.

$$V_t = \left(V_{TAFC_1}/D\right) \cdot d_{voy} \tag{4.46}$$

In which:

V_t	Minimal volume of fuel in tank	[m3]
D	Annual distance sailed	[nm]
d_{voy}	Maximal voyage distance to cover 90% of routes	[nm]

$$V_{TAFC_1} = \left(m_{TAFC_1} \cdot U_f\right) / U_{vf} \tag{4.47}$$

In which:

V_{TAFC_1}	Volume annual fuel consumption main engine of alternative fuel	[m3]
U_{vf}	Volumetric energy density of (specific) fuel	[GJ/m3]

$$m_t = \left(m_{TAFC_1}/d\right) \cdot d_{voy} \tag{4.48}$$

In which:

m_t	Minimal mass of fuel in tank	[t]

The change in CO_2 mass emitted is based on the energy content in relation to its carbon content, and is calculated in equation 4.49. In this calculation, the CO_2 emission of the required pilot fuel is also taken into account. The change in EU ETS cost are calculated by equation 4.50. The change in fuel cost is calculated based on fuel price of alternative fuels, and its fuel mass, presented in equation 4.51.

Based on these costs, and the financial costs described in section 4.4, the annual cash flow for each alternative fuels is calculated by equation 4.52.

$$\Delta m_{CO2m} = \left(C_{f0} \cdot m_{TAFC0}\right) - \left(C_{f1} \cdot m_{TAFC1} + PF_{\%}\left(C_{f0} \cdot m_{TAFC0}\right)\right) \quad (4.49)$$

In which:

Δm_{CO2m}	Change in mass CO2 emitted	[tCO2]
C_{f0}	Fuel carbon factor original fuel	[tCO2/t]
C_{f1}	Fuel carbon factor alternative fuel	[tCO2/t]

$$\Delta C_{EUETSm} = (P_{EUETS} \cdot \Delta m_{CO2m})(V_{EU} + 0.5V_{EU,nonEU}) \quad (4.50)$$

In which:

ΔC_{EUETSm}	Change in EU ETS cost	[EUR]
$P_{EU\ ETS}$	EU ETS Allowance price	[EUR/tCO2]
V_{EU}	Percentage voyages between EU ports	[-]
$V_{EU,nonEU}$	Percentage voyages between EU and non EU ports	[-]

$$\Delta C_{fuelm} = (P_{\text{fuel 1}} \cdot m_{\text{TAFC1}} + PF_{\%}\,(P_{\text{fuel 0}} \cdot m_{\text{TAFC0}})) - (P_{\text{fuel0}} \cdot m_{\text{TAFC0}}) \quad (4.51)$$

In which:

$\Delta C_{\text{fuel } m}$	Fuel cost increase or reduction	[EUR]
$P_{\text{fuel 1}}$	Fuel price alternative fuel	[EUR/t]
P_{fuel0}	Fuel price diesel/gas oil	[EUR/t]

$$CF_{\text{m}} = \Delta C_{\text{fuel } m} + \Delta C_{\text{EU ETS } m} - AR_m - C_{im} - OPEX_m \quad (4.52)$$

In which:

CF_{m}	Annual cash flow of measure	[EUR/yr]

The effects of alternative fuel strategies on the EEXI depend on the carbon factor and SFC of the alternative fuel, as presented in equation 4.53.

$$\text{New Attained EEXI} = \frac{\left(P_{ME} \cdot C_{f1} \cdot SFC_{ME1}\right) + (P_{AE} \cdot Cf_{AE} \cdot SFC_{AE})}{C \cdot S} \quad (4.53)$$

In which:

C_{f1}	Fuel carbon factor alternative fuel	[tCO2/t]
SFC_{ME1}	SFC main engine of alternative fuel	[g/kWh]

The effects of alternative fuel strategies on the CII value depend the amount of alternative fuel mass, and carbon factor of the alternative fuel. The calculation of the adjusted CII is presented in equation 4.54.

$$\text{New Attained CII} = \frac{\left(m_{TAFC1} \cdot C_{f1}\right) + (FC_{AE} \cdot Cf_{AE})}{C \cdot d} \quad (4.54)$$

In which:

m_{TAFC_1}	Annual fuel consumption main engine of alternative fuel	[t]
C_{f1}	Fuel carbon factor alternative fuel	[tCO2/t]

4.8. Model verification and validation

Model verification is performed to ensure that the computational methods and their implementation in the Comparison Tool are applied correctly. The verification methods used in this report are based on Sargent [2012], and consists of analysing the results of various tests and evaluations. First of all, data relation correctness is tested by evaluating input-output relationship of the calculation methods and assumptions listed in sections 4.1 through 4.7. And secondly, extreme condition test are performed to evaluate correctness of the computational method in the Comparison Tool. Furthermore, key outputs are manually reviewed for their correctness. The evaluation of the model verification is presented in Appendix H.

Model validation is performed to determine the accuracy and applicability of the outputs of the Comparison Tool. The quality of the outputs of the Comparison Tool is highly dependent on the input values and assumptions made in various calculation methods. Therefore the validity of the input values must be examined. This is achieved by a literature data review, historical data validation and face validity based on validation methods by Sargent [2012]. In addition, attained CII and EEXI values in the Comparison Tool are compared to results by the CII and EEXI Calculator by Lloyd's Register [LloydsRegister, 2023]. The evaluation of the (conceptual) model verification is presented in Appendix I.

5. Case study

A case study is presented in which a selection of representative short-sea vessels are analysed for their compliance to CII and EEXI regulations. Additionally, the financial viability of emission reducing measures are compared for these vessels and their effects on CII and EEXI are determined. Section 5.1 presents the data input of the short-sea reference vessels for the case study. Section 5.2 presents the fuel, EU ETS and TCE price scenarios for which the simulations are performed. The results of the case study are presented in section 5.3.

5.1. Data input of the short-sea reference vessels

To investigate the effect of measures on regulatory compliance, a case study is performed for five representative short-sea vessels that together represent 75% of the short-sea fleet till 15000 DWT. Based on the short-sea market analysis in section 2.2 three dry cargo vessels are selected with a transport capacity 3850, 8000 and 14500 DWT. In addition, one product tanker with a transport capacity 7050 DWT and one container vessel with a transport capacity 750 TEU / 9300 DWT are selected. A benefit of this selection is that an increase of vessel size within a single segment is covered, and multiple vessel types are considered.

The data inputs for the reference short-sea vessels in the Comparison Tool have a large impact on the result. In order to gain results that are in line with reality, the inputs in the tool must be an accurate representation the technical and operational characteristics of each reference vessel. The technical inputs are obtained from technical data sheets provided by shipbuilding companies [Damen, nd] (Fig. 2.1). Operational data for the reference vessels is obtained from the THETIS database. The THETIS database is a platform in which individual vessels report their CO_2 emission according to EU regulations [EU, 2016].

Actual operational data from THETIS of 222 vessels for the reporting year 2021 is presented in Appendix J for operational inputs: annual fuel consumption, average fuel consumption when at sea, number of days at sea/in port, annual distance travelled and % voyages between EU/EU-non EU ports. Some input parameters must be estimated as not all required operational parameters are reported in THETIS. The annual distance travelled is estimated based on the values from THETIS based on the annual average fuel consumption per distance, the total fuel consumption per year, number of days sailing per year, and the assumption that fuel consumption in port is 10% of fuel consumption when sailing. A formulation of this methods is presented in equation 5.1. The operational data from THETIS in Appendix J provides insights into the operation of vessels per vessel type and dead-weight tonnages. Based on this information the operational inputs of the reference vessel in the Comparison Tool are determined. These operational inputs are; the annual fuel consumption, days at sea per year, distance per year, % voyages sailed between EU ports, % voyages sailed between EU and non-ports. The values for these inputs for each reference vessel are presented in Table 5.2.

$$
\begin{aligned}
D_s * FC_s + D_p * FC_p &= TFC_{yr} \\
D_p &= (365 - D_s) \\
FC_p &= 0.1 * FC_s
\end{aligned}
\tag{5.1}
$$

D_s	Days at sea per year	[days]
D_p	Days in port per year	[days]
FC_s	Fuel consumption when at sea	[t/day]
FC_p	Fuel consumption when in port	[t/day]
TFC	Total annual fuel consumption	[t]

Other data inputs for the reference vessels include the speed estimation at theoretical operation point of the engine, and hull coefficients needed for the resistance estimation method required for the analysis of the capacity increase measures discussed in section 4.5. The ship speed at 75% MCR (vref) is estimated by the maximal ship speed provided in the technical data sheets of the reference vessel [Damen, nd] using the cubic relation between ship speed and main engine power. The block-coefficients for the five reference vessels are estimated based on research by Shah [2016]. Using the Holtrop-Menen method, the speed estimation at a constant ship resistance is calculated. The inputs for all parameters and coefficients for the reference vessels are presented in Table 5.2. Interestingly, a DWT capacity increase of 10%, 20%, and 30% hardly reduces the speed of the vessel. This can be explained by a decrease in wave making resistance when the L/B ratio increases. The effects of DWT capacity increase on the speed of the reference vessels are presented in Table 5.1.

Vessel	**% DWT capacity increase**	**Operating speed (max) [kn]**	**% speed reduction**
Dry cargo 8000 dwt	0	13.5	0.0
	10	13.4	-0.7
	20	13.3	-1.5
	30	13.2	-2.2
Dry cargo 14500 dwt	0	15	0.0
	10	14.9	-0.7
	20	14.8	-1.3
	30	14.7	-2.0

Table 5.1.: Speed reduction for a DWT capacity increase of 10%, 20% and 30% for the dry cargo 8,000 and 14,500 dwt based on the Holtrop-Mennen resistance estimation method. The other three short-sea reference vessel have negligible small speed reductions for the DWT capacity increase range.

Vessel input parameters	Dry cargo vessel	Dry cargo vessel	Dry cargo vessel	Product Tanker	Container vessel
Capacity [dwt]	3850	8000	14500	7050	9300
Capacity [gt]	2550	5750	9850	4350	7950
Speed - 100% MCR [kn]	12	13.5	15	12	17
Speed - 75% MCR (Vref) [kn]	10.9	12.3	13.6	10.9	15.4
Ice-class	n/a	n/a	n/a	n/a	n/a
Tank capacity [m3]	n/a	n/a	n/a	7750	n/a
Block coefficient (Cb)	0.75	0.75	0.75	0.8	0.67
Water plane area coefficient (Cwp)	0.83	0.83	0.83	0.87	0.78
Midship Section Area Coefficient (Cm)	0.992	0.992	0.992	0.996	0.980
Beam (B) [m]	13	16	20	17	22
Draft max (T) [m]	5	7	8	6.5	7.5
Length overall (Loa) [m]	90	120	145	105	140
Propulsion type ME	Conventional	Conventional	Conventional	Conventional	Conventional
Is the engine derated	No	No	No	No	No
Max. Continuous Rating ME (MCR)	1100	3000	6000	2650	6000
SFC ME - at 75% MCR	Calculated based on engine type and MCR				
Engine type	MSDE	MSDE	MSDE	MSDE	MSDE
Fuel type ME	ULSFO	ULSFO	ULSFO	ULSFO	ULSFO
Annual fuel consumption (ME) [t]	1400	1350	1300	1400	2400
SFC AE - at 50% MCR	215	215	215	215	215
Fuel type AE	D/G oil	D/G oil	D/G oil	D/G oil	D/G oil
Annual fuel consumption AE [t]	130	195	230	255	335
Days at sea (annual)	180	160	145	140	153
Days in port (annual)	185	205	220	225	212
Distance (annual) [nm]	38000	34500	28000	25250	34000
% voyage between EU ports	53	41	26	38	39
% voyage between non-EU ports	6	6	5	13	8
% voyage between EU and non-EU ports	41	53	69	25	53
Max. distance between refueling (to cover 90% of routes) [nm]	1200	1500	2000	1500	1000

Table 5.2.: Technical and operation inputs for the short-sea reference vessels. Data sources; technical [Damen, nd], ship-coefficients [Shah, 2016] [Papanikolaou, 2014], operational [Eurostat, 2022]. (Abbreviations: Specific Fuel Consumption (SFC), Medium Speed Diesel Engine (MSDE), Main Engine (ME), Auxiliary Engine (AE), Diesel/Gas oil (D/G oil))

5.2. Price scenarios

Price trajectories for fuel prices, EU ETS prices and TCE prices are estimated for a low case, base case and high case. The low case represent a worst case scenario in which prices negatively affect the financial viability of measures. The base case is the expected price trajectory. And the high case is a scenario in which prices are more favorable for the financial viability of measures. The price scenarios are based on the actual prices (Jan. 2023) for the year 2023, after which prices follow different price trajectories for low case, base case and high case scenarios. Fuel, EU ETS and TCE prices are assumed to move linearly towards a long-term price in a five year period. An overview of the price scenarios is presented in Table 5.3.

Fuel prices

ULSFO is set as the benchmark fuel, as this fuel is obligatory for vessels sailing in ECAs, such as the North Sea and Baltic area. In the low case, a low fuel price is chosen as this reduces fuel cost reduction by a measure. The fuel price is set at 630 $/t$ for the year 2023, which is the actual fuel price (25/01/2023). The low case assumes that the fuel price will decrease to 415 $/t$, based on historical low prices. The base case price moves towards an expected 700 $/t$. For the high case fuel prices increase towards 1250 $/t$, the all-time high. The historical prices of ULSFO are presented in Appendix N.

The price inputs for alternative fuels are based on long term average price and are fixed for the low, base and high case scenario and are; 231 €/t methanol, 796 €/t ethanol, 712 €/t LNG, 496 €/t LPG and 2020 €/t hydrogen. This method neglects price dependence between ULSFO prices and alternative fuel prices. An improved version of the Comparison Tool could account for the interaction between ULSFO price levels and alternative fuel prices for the low, base and high case scenario.

EU ETS prices

The EU ETS allowance price provides a financial incentive to reduce CO2 emissions. The low-case therefore assumes a low EU ETS price, and the high case a high price. The EU ETS price is set at 86 €$/tCO_2$ in 2023, which is the actual price (25/01/2023). In reality, the prices are expected to rise due to an increase in demand due to entry into force of regulations [Rabobank, 2022]. While the supply of ETS allowances is not expected to increase at the same rate [Rabobank, 2022]. For the low case, prices are assumed to remain at the same level, at a price of 86 €$/tCO_2$. The base case assumes a long-term price of 105 €$/tCO_2$, following the trend of the price increase and leveling off over a period of five years. The value for the high case is difficult to determine, as multiple sources predict varying high case values. For the high case, the price is assumed to rise to 140 €$/tCO_2$. This presents a relatively high estimate compared to various 'high-case' predictions of €129, €90 €108 by Pietzcker [2021] EURACTIV [2021] Bloomberg [2021]. The historical prices of EU ETS are presented in Appendix N.

TCE Rates

TCE rates have impact on the financial viability of slow steaming and capacity increase. The TCE rates are based on historical average TCE rates from the database of NESEC and the year-average TCE rates from the database of Clarksons. The historical TCE rates for the five reference vessels can found in Appendix N.

Since TCE rates vary per individual vessel, the rates in 2023 vary for the low, base and high-case scenarios. All rates move towards a long-term average, in which rates are higher for the high case and lower for the low case.

This choice for this scenario setup favors slow steaming in the low case and favors the installation of technical measures in the high case. This is due to the rise in opportunity cost when TCE rates rise. Interestingly, the low case scenario in which fuel prices are low and TCE are low, is extreme. Since TCE rates will actually increase due to lower fuel costs when the fuel price is low, this is inherent in the calculation of the TCE rate. This interaction between fuel price, EU ETS price and TCE rates is explained in more detail in the Appendix O.

Price inputs	Scenario	Actuals	2023	2024	2025	2026	2027	2028	...	2049
ULSFO price	low case	630	630	587	544	501	458	415	...	415
	base case	630	630	644	658	672	686	700	...	700
	high case	630	630	754	878	1002	1126	1250	...	1250
EU ETS price	low case	86	86	86	86	86	86	86	...	86
	base case	86	86	90	94	97	101	105	...	105
	high case	86	86	97	108	118	129	140	...	140
TCE rate	low case	6500	4100	3880	3660	3440	3220	3000	...	3000
Dry cargo 3850 dwt	base case	6500	5000	4650	4300	3950	3600	3250	...	3250
	high case	6500	6500	5900	5300	4700	4100	3500	...	3500
TCE rate	low case	-	6000	5560	5120	4680	4240	3800	...	3800
Dry cargo 8000 dwt	base case	-	8000	7305	6610	5915	5220	4525	...	4525
	high case	12500	12500	11050	9600	8150	6700	5250	...	5250
TCE rate	low case	-	6500	6200	5900	5600	5300	5000	...	5000
Dry cargo 14500 dwt	base case	-	7750	7275	6800	6325	5850	5375	...	5375
	high case	13000	13000	11550	10100	8650	7200	5750	...	5750
TCE rate	low case	-	11000	10500	10000	9500	9000	8500	...	8500
Product Tanker 7050 dwt	base case	-	11500	10975	10450	9925	9400	8875	...	8875
	high case	12000	12000	11450	10900	10350	9800	9250	...	9250
TCE rate	low case	-	7000	6600	6200	5800	5400	5000	...	5000
Container vessel 9300 dwt	base case	-	8000	7475	6950	6425	5900	5375	...	5375
	high case	16500	16500	14350	12200	10050	7900	5750	...	5750

Table 5.3.: Price scenarios for ULSFO [€/t], EU ETS [€/tCO2], TCE [€/day] (Actuals based on [Clarksons, 2022] [Nesec, 2022])

5.3. Results

Regulatory compliance of the reference vessels is presented in section 5.3.1. Feasibility results for alternative fuel strategies are presented in section 5.3.2. The method of presentation of cost-effectiveness results is discussed in section 5.3.3. The effect of measures on regulatory compliance and their financial viability for all reference vessels are presented in sections 5.3.4 to 5.3.8. A summary of the cost-effectiveness of high potential solutions is given in section 5.3.9. Finally, section 5.4 presents the conclusions of the case study.

5.3.1. Compliance of short-sea reference vessels with CII, EEXI, EU ETS regulations

The attained CII and EEXI ratings for the short-sea reference vessels are presented in Tables 5.4 and 5.5. The general cargo vessel with capacity 3850 DWT and product tanker with capacity 7050 DWT are both excluded from CII regulations. The general cargo vessels with capacity 8000 and 14500 DWT have a rating C and B in 2023 and therefore comply to CII regulation. However, due to increasingly strict CII requirements the 8000 DWT vessel will have a E-rating in 2030. Which means that this ship must increase its energy efficiency towards 2030 to obtain a C or D-rating at least.

The container reference vessel with capacity 750 TEU/9300 DWT has an CII rating E in 2023 and 2030. This ship must take immediate actions to increase its energy efficiency within a year in order to remain in operation.

All of the reference vessels except the container vessel must comply to EEXI regulations. As Table 5.5 shows, all vessels are well below the required rating and no immediate actions have to be taken to improve their EEXI rating.

Vessel	**Does this vessel fall under the CII regulations?**	**Attained CII [gCO2/tnm]**	**Rating 2023**	**Rating 2030***
Dry cargo 3850 dwt	NO	n/a	n/a	n/a
Dry cargo 8000 dwt	YES	17.6	C	E
Dry cargo 14500 dwt	YES	11.9	B	C
Product Tanker 7050 dwt	NO	n/a	n/a	n/a
Container vessel 750 TEU/9300 dwt	YES	27.3	E	E

Table 5.4.: Compliance of short-sea reference vessels with CII regulations (*assumed same increase in reduction factor (Z) of period 2021-2026 for period 2026-2030)

Vessel	**Does this vessel fall under the EEXI regulations?**	**Attained EEXI [gCO2/tnm]**	**Required EEXI [gCO2/tnm]**
Dry cargo 3850 dwt	YES	11.8	17.8
Dry cargo 8000 dwt	YES	13.7	17.8
Dry cargo 14500 dwt	YES	13.6	17.8
Product Tanker 7050 dwt	YES	14.7	21.9
Container vessel 750 TEU/9300 dwt	NO	26.8	n/a

Table 5.5.: Compliance of short-sea reference vessels with EEXI regulations

The cost for EU ETS allowances for the reference vessels are presented in Table 5.6. Note that these values are based on both carbon emitted and the operational area inputs (Tab. 5.2). This explains the higher cost for small general cargo vessels, due to its more frequent trade between EU ports. The general cargo vessel of capacity 3850 DWT and the product tanker are excluded from EU ETS regulations as these vessels are below 5000 GT. The figure shows that the EU ETS costs are significant and illustrates the incentives for shipowners to reduce the CO_2 emissions of their vessels.

Vessel	Does this vessel fall under the EU ETS regulations?	Cost per year*
Dry cargo 3850 dwt	NO	€372,000 (hypothetical value)
Dry cargo 8000 dwt	YES	€345,000
Dry cargo 14500 dwt	YES	€306,000
Product Tanker 7050 dwt	NO	€226,000 (hypothetical value)
Container vessel 750 TEU/9300 dwt	YES	€485,000

Table 5.6.: EU ETS cost per reference vessel under business as usual situation (*EU ETS fully phased in, EUA price of 105 [EUR/tCO2] and operational profiles as specified in Appendix G)

5.3.2. Feasibility results for alternative fuels

Literature indicates that storage requirements of alternative fuels is one of the key feasibility parameters [DNV, 2019a]. Comparing fuel mass and volume of alternative fuels with fuel storage facilities on (conventional) short-sea reference vessels indicate the feasibility of alternative fuel strategies on short-sea vessels.

The required fuel mass and volume for alternative fuels are compared in Figures 5.1 and 5.2. Furthermore, the maximal mass and volume of ULSFO that the conventional reference vessels are able to carry are presented, which provides a benchmark for the comparison of alternative fuel with conventional fuels. The result are calculated for the five reference vessel to cover 90% of the voyages distances on a full fuel tank. The results in Figures 5.1 and 5.2 therefore provide a minimal mass and volume. Feasibility of alternative fuels is determined based on the required mass and volume of tank + fuel mass and volume of alternative fuels, compared to the mass and volume of the conventional vessels. This method neglects fuel-specific requirements (safety, location etc.) of class societies (Appendix B), but provides a good first method of comparison.

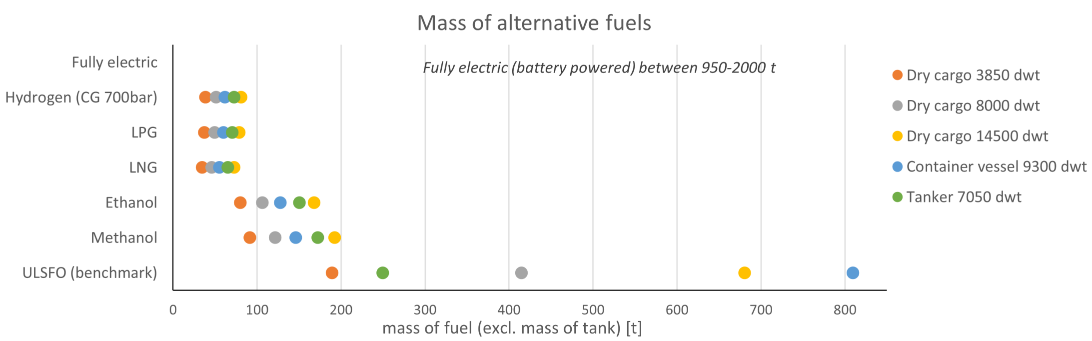


Figure 5.1.: Mass of alternative fuels (excl. mass of fuel tank) for the five short-sea reference vessels, and the fuel capacity of the conventional short-sea reference vessels using ULSFO.

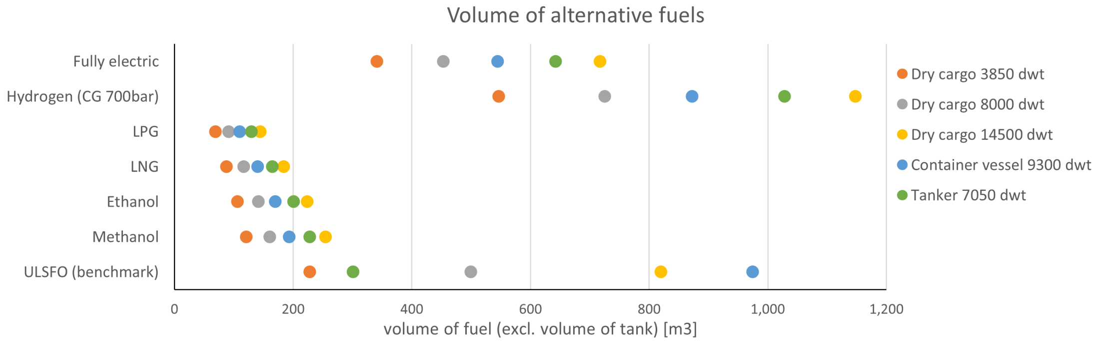


Figure 5.2.: Volume of alternative fuels (excl. mass of fuel tank) for the five short-sea reference vessels, and the fuel capacity of the conventional short-sea reference vessels using ULSFO.

When alternative fuels are compared for their mass, hydrogen (compressed gas at 700bar), LPG, LNG, ethanol and methanol have a relatively low mass compared to the benchmark storage facilities of the benchmark vessel using ULSFO. However, alternative fuels hydrogen, LPG and LNG have additional mass requirements due to their special storage tank. The total weight of fuel + tank are approximately 15 times the fuel mass for hydrogen alone, and about twice that for LNG and LPG. This is based on the data of alternative fuels provided in Figure 2.4 [DNV, 2019a]. Therefore, hydrogen is not considered the most obvious solution when compared to other carbon reducing solutions. LNG and LPG are feasible options as the total weight of fuel and tank is similar to the benchmark fuel storage capacities. Furthermore, fully electric battery powered propulsion requires a battery mass between 950-2000 tonnes. This weight is significantly higher than the benchmark, and therefore significant changes to the ship design have to be made to make this energy carrier technical feasible on short-sea ships. Hence, battery powered short-sea vessels are in this report not considered the most obvious solution when compared to other carbon reducing solutions from a technical feasibility perspective.

When alternative fuels are compared for their volume, alternative fuels LPG, LNG, ethanol and methanol have low volume requirements compared to the benchmark fuel (ULSFO). However, alternative fuels hydrogen, LPG and LNG have additional volume requirements due to their special storage tank. When the volume of the fuel tank is taken into account, the hydrogen volume requirements are approximately twice that of the fuel volume alone. For LNG and LPG, the volume requirements increase approximately by a factor of 1.7 and 1.3 compared to the fuel volume alone. Based on Figure 2.4 [DNV, 2019a]. Therefore, hydrogen is not considered a obvious solution when compared to other carbon reducing solution due to its large volume requirements. LNG and LPG are feasible options as the total volume of fuel and tank is similar to the benchmark fuel storage capacities. Fully electric battery powered propulsion requires additional volume for some short-sea vessels. Because volume requirements of fully electric battery powered propulsion is similar to fuel storage capacity of conventional short-sea vessels, battery powered vessels are considered feasible from a volume perspective.

In short, technical feasibility of fully electric battery powered short-sea vessels is limited by mass requirements. Furthermore, technical feasibility of hydrogen as an energy carrier on short-sea ships is limited by both mass and volume requirements. Both fuels are not considered obvious solutions to reduced emissions on short-sea vessels, when compared to other carbon reducing measures. Alternative fuels LPG, LNG, ethanol and methanol are considered technically feasible, when fuel storage mass and volumes are calculated to cover 90% of the voyages distances on a full fuel tank for the short-sea reference vessels.

5.3.3. Method of presentation of cost-effectiveness results

To give clear insight in the data obtained from the Comparison Tool, the results are presented for a selection of measures. This selection is made based on the effect measures have on CII and EEXI regulations and the NPV of their investment. The NPV of measures are compared to their effect on CII and EEXI for each reference vessel. This presents a Pareto front of cost-effective options, an example of this is presented in Figure 5.3 for the general cargo reference ship with capacity 8000 DWT. Cost-effectiveness figures for all the reference vessels are presented in Appendix P.

Because the CII is the regulatory bottleneck for most vessels (Fig.5.4), the top 10 measures with the largest effect on the CII are compared for their cost-effectiveness in more detail. The measures hydrogen and battery power have the largest reduction effect on CII of all measures, however due to their extreme negative NPVs these are not included in the top 10. In addition, ethanol is not presented in the results due to its increase in CII and its extreme negative NPV. The increase in CII for ethanol can be explained by its low effective efficiency and its high carbon content relative to its energy density.

The results for the impact of measures on the EEXI are explained in detail for one reference vessel (general cargo 3850 dwt), but not for other reference vessels as all vessels amply comply to EEXI regulations. The results for the impact of measures on the EEXI for all reference vessels can be found in Appendix Q.

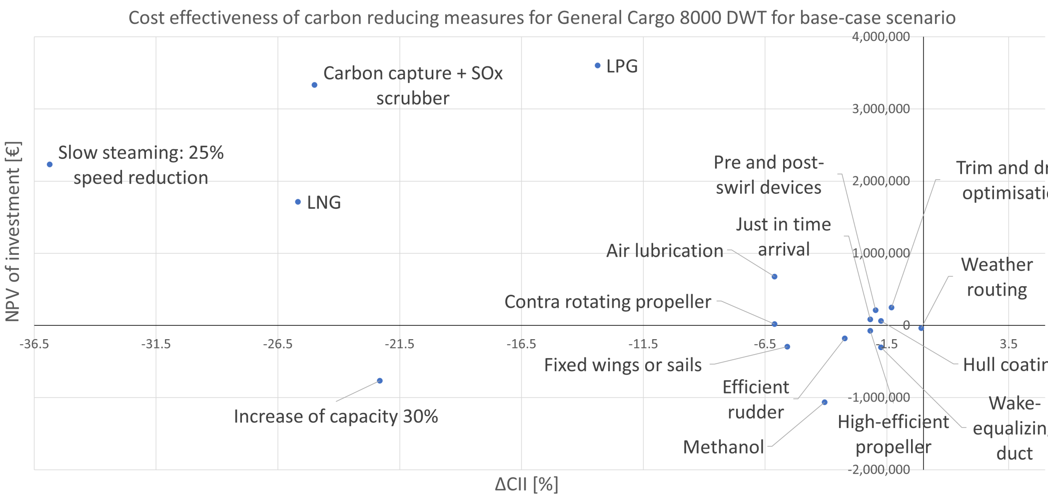


Figure 5.3.: Cost effectiveness for carbon reducing measures of General Cargo 8000 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol which have corresponding NPVs of -72, -115 and -17 million euros)

5.3.4. Results General cargo 3850 DWT vessel

The effect of measures on the EEXI are presented in Figure 5.4. This reference vessel amply complies with the regulations. Interestingly, methanol results in an increase in EEXI which can be explained by its effective efficiency and its high carbon content relative to its energy density. The effect of measures on the CII is not presented for this vessel as it falls outside the regulations.

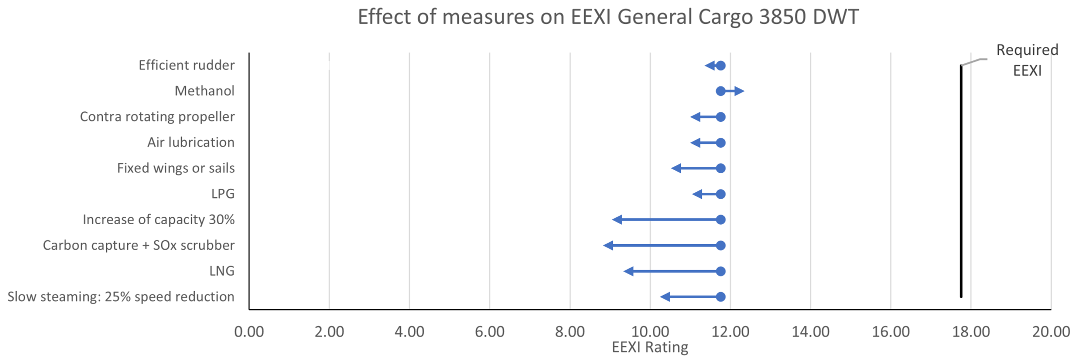


Figure 5.4.: Effect of measures on the EEXI of the general cargo 3850 DWT reference vessel

The NVP for measures presented in Figure 5.5 show that alternative fuel strategies have a large variation in NPV between low and high-case price scenarios. This can be explained by the method of calculation, which varies the price for the conventional compared for the low and high case to a constant price level for the alternative fuel. In practice, the price levels of alternative fuels and conventional LSFO may influence each other due to the interdependence of price levels. Moreover, carbon-capture and storage does not present value for low and high-case. This is due to the exclusion from the EU ETS regulation and its independence on fuel price and TCE rates.

Furthermore, Figure 5.5 shows that multiple measure have positive NVP for all price scenarios; slow-steaming, carbon-capture and storage, capacity increase, fixed wings and sails, and air lubrication. Of these measures, slow-steaming, carbon-capture, capacity increase and fixed wings reduce CO_2 emissions significantly and are most promising for this vessel. The alternative fuel strategy LNG also offers solutions to reduce emission significantly, and has a positive NPV for the base case scenario. The financial feasibility of LNG is however highly dependent on fuel prices, and therefore has a large negative NPV for the low-case price scenario.

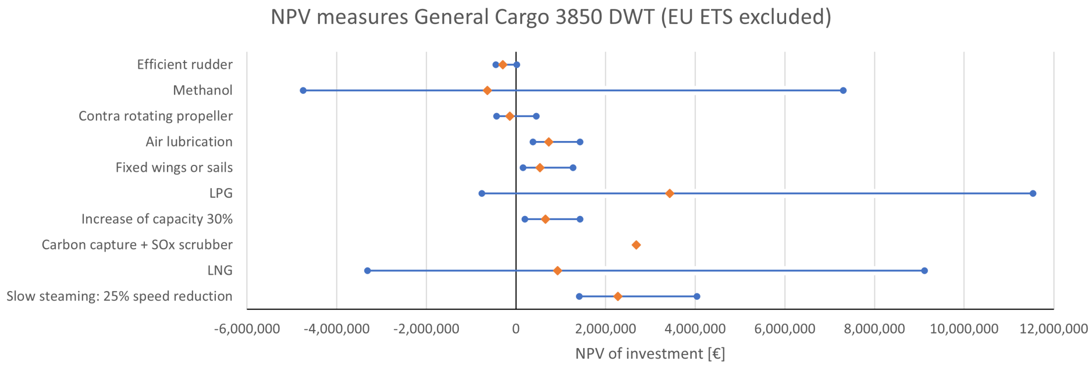


Figure 5.5.: NPV of measures for the general cargo 3850 DWT reference vessel. (orange diamond represents base case price scenarios, and the blue dots represent low and high-case scenarios)

Since this reference vessel is excluded from EU ETS regulation, a comparison is made of NPVs of measures for inclusion/exclusion of these regulations in Figure 5.6. This provides regulators with insight into the incentives that this regulation may offer to operators of this ship type and size. Logically, the inclusion of this regulation has a large (absolute) impact on NPVs of measures that results in large CO_2 reduction. Inclusion of EU ETS would therefore have higher incentives for high impact measures such as change of fuel type.

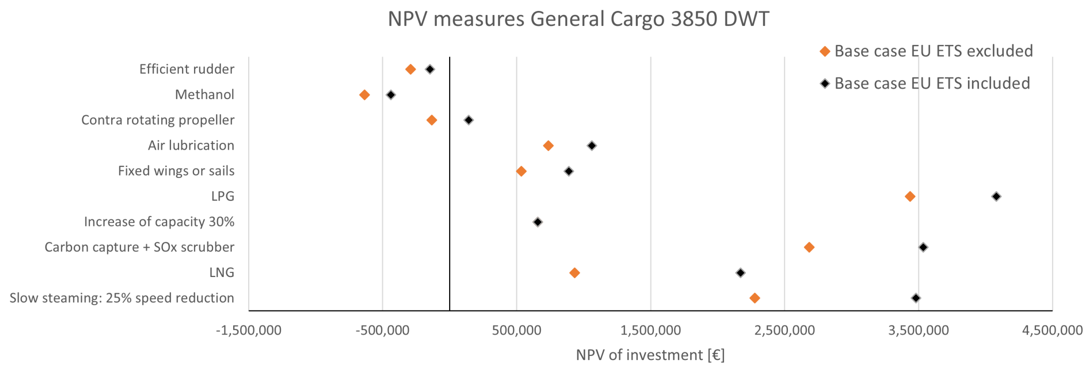


Figure 5.6.: Comparison of the NVP of measures for the general cargo 3850 DWT reference vessel for the inclusion/exclusion of EU ETS regulations (EUA price of 105 [EUR/tCO2])

5.3.5. Results General cargo 8000 DWT vessel

The effect of measures on the CII presented in Figure 5.7 show that this reference vessel has to improve its CII towards 2030. The rating must be reduced to achieve a rating of at least the E-boundary for 2030, but preferable below the D-boundary in 2030. The measures that provide solutions to achieve a C-rating in 2030 are slow-steaming, LNG, carbon-capture and storage, capacity increase and LPG. Measures that have a lower impact on CII, but provide solutions to achieve at least a D-rating are air lubrication, fixed wings or sails, methanol or retrofitting with a more efficient propeller or rudder. In the short term, this vessel complies with CII regulations and no immediate action is required.

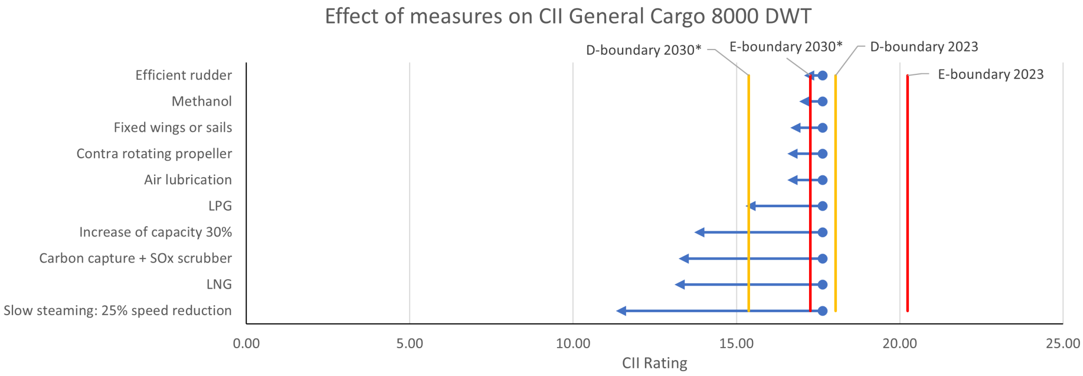


Figure 5.7.: Effect of measures on the CII of the general cargo 8000 DWT reference vessel (*assumed same increase in reduction factor (Z) of period 2021-2026 for period 2026-2030)

(*assumed same increase in reduction factor (Z) of period 2021-2026 for period 2026-2030)

The NPV for measures presented in Figure 5.8 show that of the measures that provide solutions to achieve a C-rating (2030), slow steaming and carbon-capture and storage provide robust solutions, with positive NPV for all price scenarios. The low-emission fuel strategies LNG and LPG have positive NPVs for the base scenario, but have negative NPVs for the low-case price scenario due to their dependence on fuel prices. Increasing capacity has a negative NPV. However, this measure is a more robust solution to comply to regulations compared to low-fuel strategies. Due to the lower variance between low and high-case scenarios of capacity increase compared to LNG and LPG. In addition, air lubrication offers a financially viable solution with positive NPVs for all price scenarios, although its CO_2 reduction is limited.

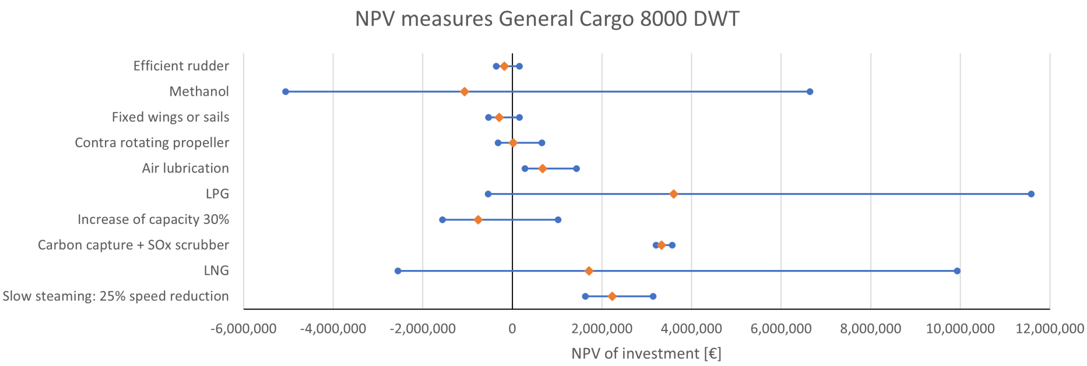


Figure 5.8.: NPV of measures for the general cargo 8000 DWT reference vessel. (orange diamond represents base case price scenarios, and the blue dots represent low and high-case scenarios)

5.3.6. Results General cargo 14500 DWT vessel

Figure 5.9 shows that this reference vessel complies with the CII regulations towards 2030. There is therefore no regulatory requirement to reduce CO_2 emission.

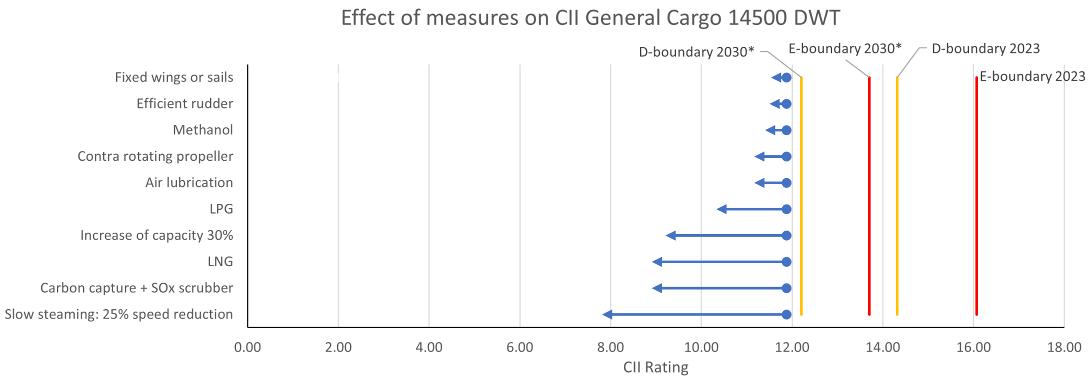


Figure 5.9.: Effect of measures on the CII of the general cargo 14500 DWT reference vessel (*assumed same increase in reduction factor (Z) of period 2021-2026 for period 2026-2030)

The NPV of measures presented in Figure 5.10 show that slow-steaming and carbon capture and storage provide robust solutions with positive NPV for all price scenarios. Technical measures have negative NPV and are therefore less suitable for this vessel.

Similarly to the results for general cargo vessels with capacity 3850 and 8000 DWT LNG and LPG have positive NPVs for the base scenario, but have negative NPVs for the low-case price scenario. Interestingly, the cost-effectiveness of capacity increase reduces for the general cargo reference vessel when DWT increases. This effect can be explained by the higher investment costs for larger vessels.

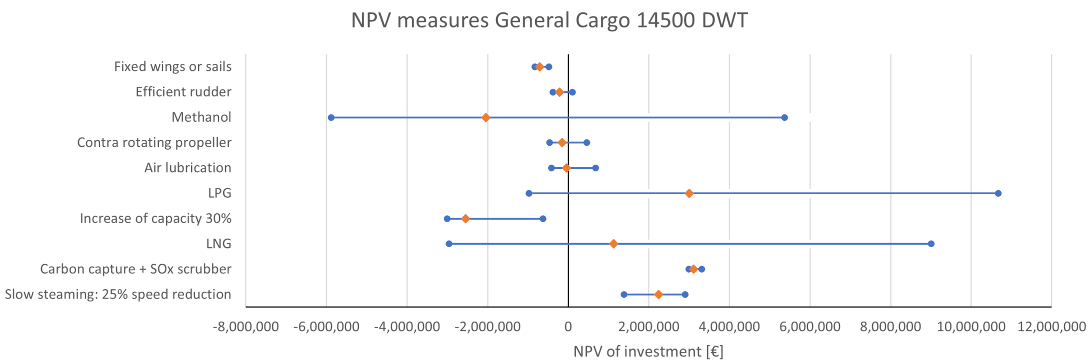


Figure 5.10.: NPV of measures for the general cargo 14500 DWT reference vessel. (orange diamond represents base case price scenarios, and the blue dots represent low and high-case scenarios)

5.3.7. Results Container vessel 750 TEU / 9300 DWT

The effect op measures on the CII presented in Figure 5.11 show that this reference vessel has to improve its CII towards 2030. The rating must be reduced to achieve a rating of at least the E-boundary for 2030, but preferable below the D-boundary in 2030. The only measures that provides a solution to achieve a C-rating in 2030 is slow-steaming. Measures that have a lower impact on CII, but provide solutions to achieve at least a D-rating are LNG, carbon capture and capacity increase.

In the short-term, this reference vessel can comply to CII by applying the measures; slow-steaming, LNG, carbon capture, capacity increase and LPG.

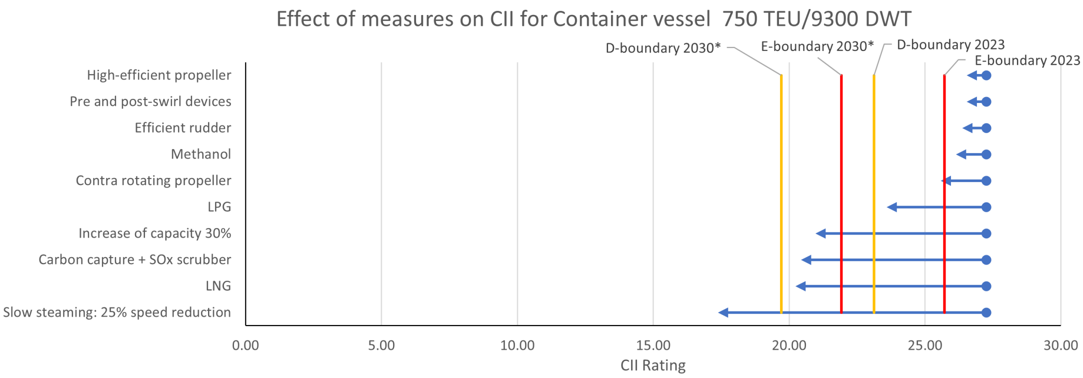


Figure 5.11.: Effect of measures on the CII of the container reference vessel 750 TEU / 9300 DWT (*assumed same increase in reduction factor (Z) of period 2021-2026 for period 2026-2030)

The NPV for measures presented in Figure 5.8 show that slow-steaming offers a financially viable solution to attain a C-rating (2030), with a positive NPV for all price scenarios. Furthermore, carbon capture provides a financially viable solution to achieve at least a D-rating in 2030.

Similarly to the results for general cargo vessels, LNG and LPG have positive NPVs for the base scenario, but have negative NPVs for the low-case price scenario. These also provide solutions to attain a C-rating (2030), but their NPVs are more volatile compared to slow-steaming and carbon capture.

Interestingly, technical measures such as flow-devices and more efficient propeller and rudder provide positive NPV for all price scenarios. While either of these measures will not reduce CO_2 enough to meet CII regulations, they do provide robust, financially viable options for this vessel type.

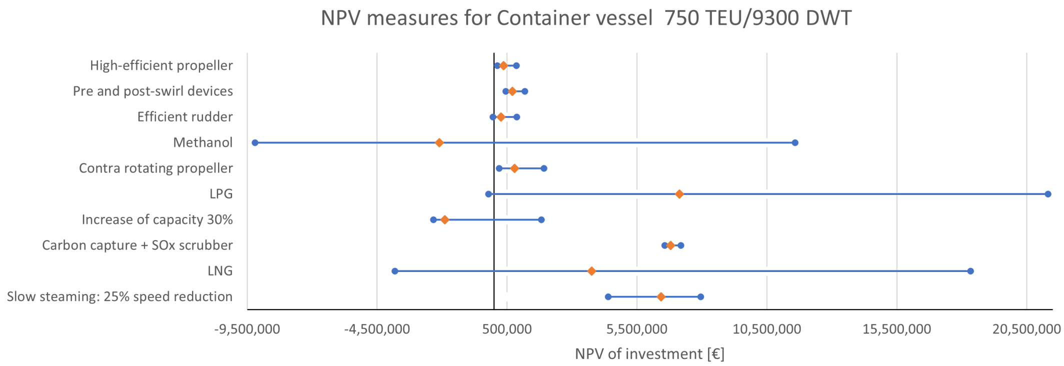


Figure 5.12.: NPV of measures for the container reference vessel 750 TEU / 9300 DWT (orange diamond represents base case price scenarios, and the blue dots represent low and high-case scenarios)

5.3.8. Results Product Tanker 7050 DWT

The effect of measures on the CII is not presented for this vessel as it falls outside the regulations. There is therefore no regulatory requirement to reduce CO_2 emission.

The NPV for the measures presented in Figure 5.13 show that financially viable measures with positive NPV for all price scenarios are; carbon capture and air lubrication. Similarly to the results for general cargo and container vessels, LNG and LPG have positive NPVs for the base scenario, but have negative NPVs for the low-case price scenario. The same applied to slow steaming. Technical measures such as more efficient propeller, rudder, wings or sails do not provide positive NPV for all price scenarios and are not considered robust, financially viable solutions.

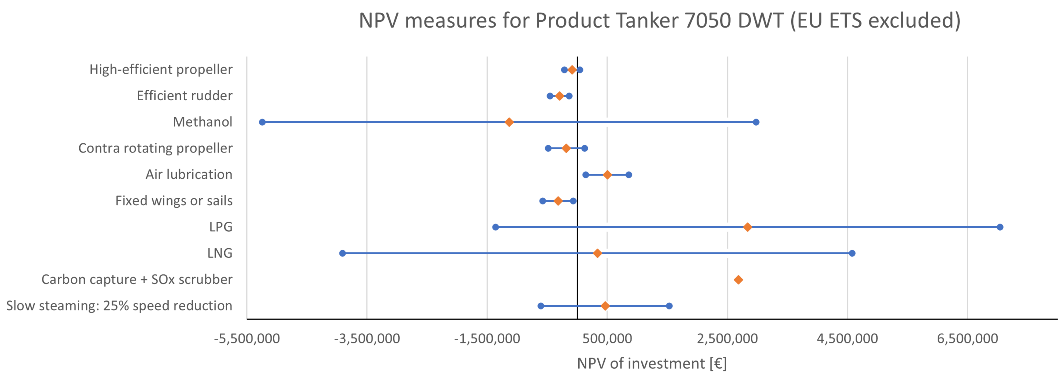


Figure 5.13.: NPV of measures for the product tanker reference vessel 7050 DWT (orange diamond represents base case price scenarios, and the blue dots represent low and high-case scenarios)

Since this reference vessel is excluded from EU ETS regulation, a comparison is made of NPV of measures for inclusion/exclusion of these regulations in Figure 5.14. This provides regulators with insight into the incentives that this regulation may offer to operators of this ship type and size. Logically, the inclusion of this regulation has a large (absolute) impact on NPVs of measures that results in large CO2 reduction. Inclusion of EU ETS would therefore have higher incentives for high impact measures such as change of fuel type.

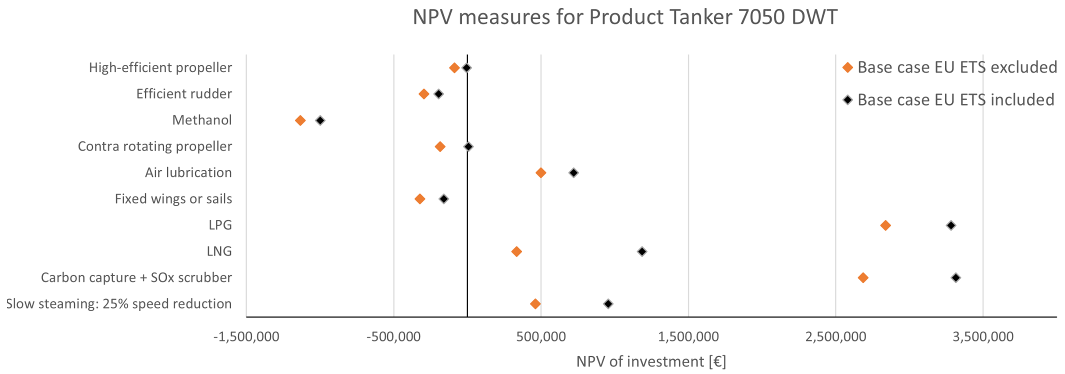


Figure 5.14.: Comparison of the NVP of measures for the product tanker 9300 DWT reference vessel for the inclusion/exclusion of EU ETS regulations (EUA price of 105 [EUR/tCO2])

5.3.9. Summary of cost-effectiveness of high potential solutions.

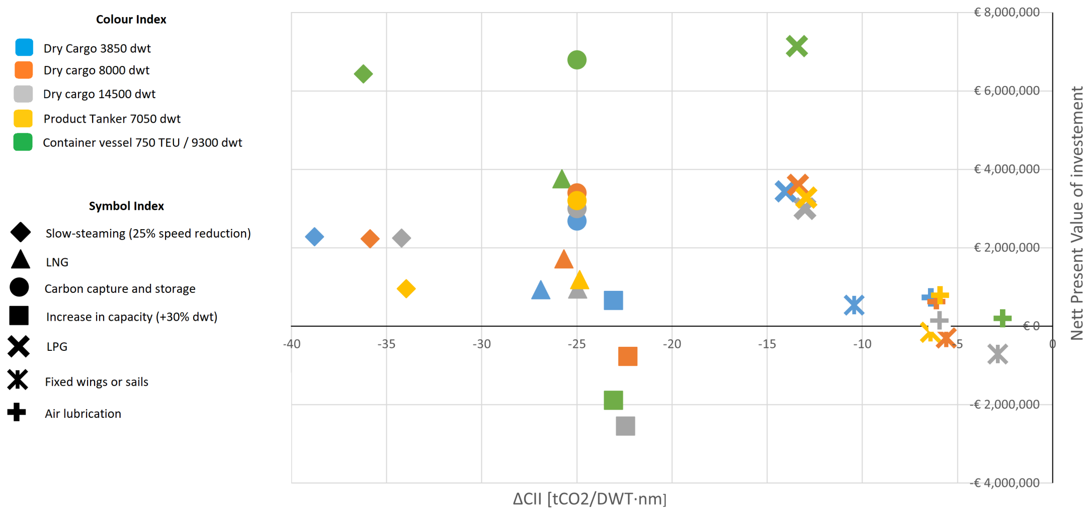


Figure 5.15.: Summary of results for all five short-sea reference vessels that offer the most cost-effective solutions to reduce CO2 emissions. (NPV for base-case EU ETS, fuel and TCE price scenario)

Figure 5.15 compares cost-effectiveness of measures for all five short-sea reference vessels. The figure shows that the effectiveness of measures to reduce CO2 emissions varies little between different ship types and sizes, with the exception of slow-steaming. These small differences are explained by the different inputs for auxiliary engine fuel consumption per vessels, on which measures has no effect (except carbon capture). The larger differences for slow-steaming between vessels can be explained by the different operational profiles (number of sailing days) per ship type and size. The net present value of measures, however, do vary significantly per vessel type and size. This mainly applies to container vessels for which the NPV of an investment in carbon reducing measures is significantly higher for the measures slow-steaming, carbon capture, LNG and LPG. This can be explained by the high annual fuel consumption of container vessels, which amplifies fuel and EU ETS cost reduction when a measure is implemented and increases the NPV of an investment in a measure.

5.4. Case study conclusion

All reference vessels in this case study amply comply with EEXI regulations. The compliance to CII depends on vessel size and type. Currently general cargo vessels of all sizes comply with CII regulations, but have to reduce their CO_2 emission towards 2030 to maintain a good rating. In addition, the results show that smaller general cargo ships comply less well with the CII regulations than larger ones. The container reference vessel (750 TEU/9,300 dWT capacity) does not comply with CII and has to reduce its CO_2 emissions immediately. The product tanker (7050 DWT) and smallest general cargo vessel (3850 DWT) are excluded from CII as their gross tonnage is below 5000 GT.

The results from the Comparison Tool show that only 7 measures provide significant CO_2 reduction that offer solutions to comply with CII regulations. These measures consist of low-emission fuel strategies; LNG, LPG, hydrogen and fully electric, and technical measures; capacity increase, carbon capture and slow-steaming (engine derating).

The low-emission fuel strategies hydrogen and fully electric do not offer financially viable solutions, with highly negative NPVs between -55 and -175 million euros. Furthermore, technical feasibility of these fuels is a major challenge and therefore these are not considered obvious solution, when compared to other carbon reducing measures. These results are based on a minimal required fuel storage capacity to cover at least 90% of single voyage distances for individual short-sea reference vessels, and present therefore a minimum cost. Alternative fuel strategies LNG and LPG provide technical feasible solutions. Furthermore, LNG and LPG offer solutions to comply to CII regulation and have a positive NPVs for the expected fuel, TCE and emission allowance price development. However, due to the dependence of financial viability of LNG and LPG on price levels, they have negative NPV for the low-case price scenarios with low ULSFO prices, low TCE rates and low EU ETS prices.

Slow-steaming and carbon capture and storage offer financially viable solutions to comply with CII. Both measures provide positive NPVs for all reference vessel under all price scenarios (except for tanker vessels). In addition, an advantage of carbon capture and storage is that its financial viability for a low or high-case price scenario only depends on EU ETS prices, resulting in a limited variance. Note that the cost-reductions of this measure results from both the reduction of EUA cost, and the price spread between LSFO and HFO. Furthermore, increase in capacity offers a solutions to reduce a ship's CII and EEXI rating significantly. Its NPVs for smaller vessels, and is negative for larger general cargo and container vessels.

The results show that installation of a single technical measures that improves propeller efficiency, rudder resistance, fixed wing or sail and air-lubrication offer insufficient CO_2 reductions to comply to CII (in the situation that a ship does not comply with CII regulations). However, they offer financially viable solutions with positive NPVs for small general cargo vessels and the container reference vessel. A combination of these measures might have an higher CO_2 reduction potential, although the effect of an individual measures might be reduced.

Furthermore, the effect of the inclusion of EU ETS on financial viability for small general cargo vessels and tanker vessel below 5,000 GT are presented. This show that the inclusion of EU ETS regulations result in higher financial incentive for shipowners to invest in measures that reduce significant amounts of CO_2 emission, such as a low-emission fuel, carbon capture and storage and slow-steaming. The inclusion of this regulation on small vessel would give incentives to shipowners to invest in technologies that reduce CO_2 significantly. However, more factors need to be taken into account when deciding whether to include the EU ETS for small short-sea vessels. One of these aspects is that there could be a modal shift from maritime to road transport due to the inclusion of EU ETS and the associated higher operational costs. Further research needs to be done, taking into account all aspects of this problem.

The use of methanol as the main fuel is not a financially solution for short-sea vessels. The NPVs for base-case scenarios are negative and there is a large variation in NPVs for low and high-case price scenarios. Cost-effectiveness of low-emission fuels is likely to be more favorable when they are compared from a well-to-wake approach instead of tank-to-wake, on which CII and EEXI regulations are based.

6. Discussion and recommendations

This research compares technical feasible CO_2 reducing measures for a set op representative short-sea vessels below 15,000 DWT for their financial viability and their effect on EEXI and CII compliance. To achieve this, a Comparison Tool is developed which determined cost-effectiveness of individual measures based on a set technical and operational ship inputs. This low-detail model provides insights in vessel specific solution to reduce CO_2 emissions for a wide range of measures; technical, operational and alternative fuels. Due to the simple setup of the model, various measure specific inputs can be revised easily by the user. The implementation of measures in the Comparison Tool are based on various estimates that influence the results, the effects of these assumptions are briefly discussed in the following text.

The Comparison Tool uses a tank-to-wake approach, as the EU and IMO regulations are based on this IMO [2012] [IMO, 2020] [EC, 2021]. Low-carbon fuels such as e-ethanol, bio-fuels etc could form a carbon-reducing solution when a well-to-wake approach is integrated in regulations.

Financial viability of measures is highly dependent on cost and CO_2 reduction assumption of individual measures, which in the Comparison Tool are estimated based on literature and data from NESEC. Since this input data is generalized for ship types and size categories, the results may be less accurate for ships with a capacity close to the category limits. Furthermore, due to scarce data on carbon capture and storage systems, effect of this system on fuel consumption are neglected in the Comparison Tool and the rough assumption is made that 25% of CO_2 is captured. The design of the model is made in such a way that costs and CO_2 reduction assumption can be revised when more data is available, providing more accurate results.

Operational data inputs for the reference vessels, such as annual fuel consumption, annual distance sailed etc, are based on the average values in 2021 for a certain vessel type and DWT from the THETIS database. Due to high TCE rates in the previous years, operational data might not represent long term average values. This might especially be applicable to container vessels which experience extreme high TCE rates [Nesec, 2023] [Clarksons, 2022]. To gain more accurate results, long term average operational data could be used.

Furthermore, the CO_2 reduction potential and financial viability of low-emission fuel strategies are roughly estimated based on the effective efficiencies of IC engines. As limited data in available of effective efficiencies of LNG, LPG, hydrogen, methanol and ethanol IC engines these inputs have higher uncertainty. An improved version of the model could include the actual efficiency of energy converters when more data becomes available.

An overview of other relevant model extensions and recommendations for future research are listed and briefly explained below.

- Comparing (fuel flexible) engine strategies. This forms robust solutions and is a method to prepare ships for stricter emission requirements in the future.

- Combining measures and their combined effect on regulatory compliance. Emission reduction through a combination of measures is uncertain and is therefore not included in this report, but may offer solutions to reduce significant amounts of emissions.
- Review cost input data of measures by experts. The costs of emission reduction measures are likely to decrease in the future due to innovation and should be regularly updated.
- Update model with new innovative emission reduction technologies in the future. The model is designed in such a way that new emission reducing measures can be easily added.
- Extend vessel list. To create more impact to achieve the carbon reduction targets of the maritime sector the model can be extended to include other vessel types and sizes. The model is designed in such a way that vessel types and size can be easily added.
- Include well-to-wake emissions of alternative fuels and compare carbon reduction potential of fuels to tank-to-wake results. This provides regulators with information about the incentives that a well-to-wake approach provides to shipowners.
- Include reduction effect of measures on other ship emission than CO_2. This provides insight into solutions for ships to move towards emission-free shipping.

7. Research conclusions

This research compares technical feasible CO_2 reducing measures for a set op representative short-sea vessels below 15,000 DWT for their cost and their effect on EEXI and CII compliance. To achieve this, a Comparison Tool is developed which compares individual measures for cost-effectiveness based on a set technical and operational ship inputs. This low-detail model provides insights in vessel specific solution to reduce CO_2 emissions for a wide range of measures; technical, operational and alternative fuels. To asses viable solution for short-sea ships, this reports has determined the technical feasibility of emission reducing measures for a selection of representative short-sea vessels. Furthermore, to compare the financial viability of measures, the net present value of measures is quantified based on cost of capital, operational cost, fuel cost reduction, EU ETS cost reduction and the effect measures have on the income of the vessel. This report is the first to introduce and specify such a comprehensive comparison framework. Due to the simple setup of the model, various measure specific inputs and price assumption can be revised easily by the user, supporting shipowners and financiers in their investment decisions.

The results show that short-sea vessel amply comply with EEXI regulations. The compliance with CII depends on vessel type and size. Short-sea general cargo vessels of all sizes currently comply with CII regulations, but have to reduce their CO_2 emission towards 2030 to maintain a good rating. In addition, the results show that smaller general cargo ships comply less well with the CII regulations than larger ones. The container reference vessel (750 TEU/9,300 dWT capacity) does not comply with CII and has to reduce CO_2 emissions immediately.

The results of the Comparison Tool show that only 7 measures provide significant CO_2 reduction that offer solutions to comply with CII regulations (when a vessel does not comply). These measures consist of low-emission fuel strategies; LNG, LPG, hydrogen and fully electric, and technical measures; capacity increase, carbon capture and slow-steaming (engine derating).

The low-emission fuel strategies hydrogen and fully electric do not offer financially viable solutions, with highly negative NPVs between -55 and -175 million euros. Furthermore, technical feasibility of fully electric battery powered short-sea vessels is limited by mass requirements and technical feasibility of hydrogen is limited by both mass and volume requirements. These results are based on a minimal required fuel storage capacity to cover at least 90% of single voyage distances for individual short-sea reference vessels, and present therefore a minimum cost, mass and volume. LNG and LPG offer financially viable solutions to comply to CII regulation and have a positive NPVs for the expected fuel, TCE and EU ETS allowance price development. However, due to the dependence of financial viability of LNG and LPG on price levels, they have negative NPV for the low-case price scenarios with low ULSFO prices, low TCE rates and low EU ETS allowance prices. Moreover, LNG and LPG are considered technically feasible, when fuel storage mass and volumes are calculated to cover 90% of the voyages distances on a full fuel tank for the short-sea reference vessels.

Slow-steaming offers financially viable solutions to comply with CII. It provides positive NPVs for all reference vessel under all price scenarios (except for tanker vessels). Please note that the feasibility of speed reduction for slow-steaming may be limited by factors other than those considered in this study (loss of income and change in EU ETS and fuel cost). These factors consist of requirements for cargo to be unloaded at the port at a certain time, or time requirements to load the next cargo (etc.), which can limit the extent to which a ship can reduce its speed. Moreover, carbon capture and storage offers cost-effective solutions to comply with CII. An additional advantage of carbon capture and storage is that its financial viability for a low or high-case price scenario only depends on EU ETS allowance prices, resulting in a limited variance. Note that the cost-reductions of this measure results from both the reduction of EU ETS allowance cost, and the price spread between ULSFO and HFO. Furthermore, increase in capacity offers a solution to reduce a vessel's CII and EEXI rating significantly. Its NPV is positive for smaller vessels, and is negative for larger general cargo and container vessels.

The results in this research show that installation of a single technical measures that improves propeller efficiency, hydrodynamic efficiency, or a fixed wing or sail has insufficient CO_2 reduction potential to comply to CII (when a ship does not comply). However, they offer financially viable solution with positive NPVs for small general cargo vessels and the container reference vessel. A combination of these measures might have a higher CO_2 reduction potential, although the effect of an individual measures might be reduced.

Furthermore, the effect of the inclusion of EU ETS on financial viability for small general cargo vessels and tanker vessel below 5,000 GT are presented. This show that the inclusion of EU ETS regulations result in higher incentives for measures that reduce significant amounts of CO_2 emission, such as a low-emission fuel, carbon capture and storage and slow-steaming. The inclusion of this regulation on small vessel would give incentives to shipowners to invest in technologies that reduce CO_2 significantly.

Further development of the Comparison Tool can expand the scope to larger vessel sizes and types. Supporting shipowners and financiers in their investment decisions and creating more impact to achieve the carbon reduction targets of the maritime sector.

A. Short-Sea Vessel fleet data selection

Group	Type	Vessels	Total GT	Total DWT Tonnes	Average DWT Tonnes	Average Age	Average GT
Other Dry Cargo	Multi-Purpose	1,054	4,204,624	5,964,335	5,658	17	3,989
Other Dry Cargo	General Cargo	377	1,223,661	1,789,396	4,746	16	3,245
Tanker	Chem Parcel Tanker	317	1,596,902	2,354,551	7,427	15	5,037
FCC	Fully Cellular Container	212	1,819,869	2,191,881	10,339	16	8,584
Tanker	Chemical Bulk Tanker	90	464,328	687,261	7,636	14	5,159
Reefer	Reefer	78	722,467	757,456	9,710	26	9,262
Gas Carrier	LPG Carrier	76	361,338	395,657	5,206	12	4,754
Other Dry Cargo	Multi-Purpose/Heavy Lift Cargo	50	533,351	581,448	11,628	10	10,667
Tanker	Product Carrier	35	104,859	162,961	4,656	22	2,995
Tanker	Asphalt & Bitumen Carrier	33	176,950	206,786	6,266	12	5,362
Bulk Carrier	Cement Carrier	31	122,913	174,265	5,621	17	3,964
Gas Carrier	Ethylene/LPG	30	224,272	245,657	8,188	14	7,475
Bulk Carrier	Open Hatch Carrier	15	136,760	197,795	13,186	12	9,117
Tanker	Oil Bunkering Tanker	10	27,877	42,104	4,210	11	2,787
Bulk Carrier	Bulk Carrier	10	74,212	113,650	11,365	18	7,421
Tanker	Chemical Unknown Carrier	8	29,113	43,114	5,389	8	3,639
Gas Carrier	LNG Bunkering Vessel	7	61,996	32,661	4,665	3	8,856
Reefer	Reefer Fish Carrier	6	30,411	22,565	3,760	21	5,068
Other Dry Cargo	Heavy Lift Cargo Vessel	6	70,971	48,559	8,093	14	11,828
Tanker	Chemical & Oil Carrier	5	20,081	36,771	7,354	19	4,016
Tanker	Tanker	4	11,693	16,592	4,148	37	2,923
Reefer	Reefer/Pallets Carrier	4	14,274	14,155	3,538	32	3,568
Gas Carrier	LNG Carrier	4	47,253	30,825	7,706	3	11,813
Gas Carrier	LNG/Ethylene/LPG	4	40,420	41,764	10,441	11	10,105
Other Dry Cargo	Palletised Cargo Carrier	3	12,100	10,495	3,498	33	4,033
Miscel. Cargo	Miscellaneous Cargo	3	20,392	14,226	4,742	12	6,797
Gas Carrier	CO2 Carrier	3	7,486	10,447	3,482	17	2,495
Other Dry Cargo	Deck Cargo Carrier	2	6,033	9,533	4,766	9	3,016
Miscel. Cargo	Livestock Carrier	2	15,069	9,284	4,642	32	7,534
Tanker	Chemical Bulk Tanker	1	7,292	11,320	11,320	15	7,292
Ore/Oil Carrier	Ore/Oil Carrier	1	2,615	3,280	3,280	38	2,615
Miscel. Cargo	Fish Feed Carrier	1	1,918	2,572	2,572	6	1,918
Gas Carrier	LNG & Oil Bunkering Vessel	1	1,676	3,000	3,000	13	1,676
Bulk Carrier	Limestone Carrier	1	3,092	4,250	4,250	24	3,092
Bulk Carrier	Aggregates Carrier	1	2,680	4,316	4,316	28	2,680

Table A.1.: Data selection of short-sea vessels below 15,000 DWT operating in the North-sea and Baltic area

Group	Type	Vessels	Total GT	Total DWT Tonnes	Average DWT Tonnes	Average Age	Average GT
Other Dry Cargo	General Cargo	792	2,818,552	3,844,596	4,854	27	3,558
Other Dry Cargo	Multi-Purpose	767	3,405,233	4,641,583	6,051	20	4,439
Tanker	Chem Parcel Tanker	239	1,274,624	1,917,557	8,023	15	5,333
Tanker	Product Carrier	211	809,164	1,160,151	5,498	19	3,834
FCC	Fully Cellular Container	197	1,664,071	2,032,602	10,317	19	8,447
Tanker	Chemical Bulk Tanker	88	414,051	610,818	6,941	13	4,705
Gas Carrier	LPG Carrier	72	408,617	455,397	6,324	15	5,675
Tanker	Chemical Unknown Carrier	54	250,833	351,553	6,510	9	4,645
Bulk Carrier	Bulk Carrier	36	289,235	441,831	12,273	20	8,034
Tanker	Asphalt & Bitumen Carrier	35	186,382	223,716	6,391	12	5,325
Other Dry Cargo	Multi-Purpose/Heavy Lift Cargo	32	269,369	318,954	9,967	14	8,417
Tanker	Oil Bunkering Tanker	31	98,865	145,040	4,678	11	3,189
Bulk Carrier	Cement Carrier	31	151,001	228,091	7,357	24	4,871
Tanker	Tanker	30	145,546	220,872	7,362	24	4,851
Reefer	Reefer	23	189,384	198,139	8,614	25	8,234
Gas Carrier	Ethylene/LPG	20	149,011	172,691	8,634	15	7,450
Ore/Oil Carrier	Ore/Oil Carrier	17	48,738	60,952	3,585	35	2,866
Bulk Carrier	Open Hatch Carrier	17	133,861	198,242	11,661	16	7,874
Miscel. Cargo	Livestock Carrier	15	104,790	71,236	4,749	30	6,986
Tanker	Chemical & Oil Carrier	9	32,905	51,370	5,707	25	3,656
Tanker	Products/Multi-Purpose Cargo	7	27,496	39,123	5,589	6	3,928
Other Dry Cargo	Heavy Lift Cargo Vessel	6	58,008	44,401	7,400	25	9,668
Reefer	Reefer Fish Carrier	3	14,626	14,471	4,823	10	4,875
Bulk Carrier	Aggregates Carrier	3	7,575	14,758	4,919	24	2,525
Gas Carrier	LNG Carrier	2	16,732	9,432	4,716	0	8,366
Other Dry Cargo	Deck Cargo Carrier	1	5,264	10,000	10,000	21	5,264
Gas Carrier	LNG & Oil Bunkering Vessel	1	3,149	4,999	4,999	3	3,149
Gas Carrier	LNG/Ethylene/LPG	1	7,833	6,150	6,150	13	7,833
Gas Carrier	LNG Bunkering Vessel	1	17,600	9,000	9,000	0	17,600

Table A.2.: Data Short-sea vessels below 15,000 DWT operating in the Mediterranean and Black sea area

Data on short-sea type and size distribution in Europe for Figures 2.6 and 2.7 are collected from the World Fleet Register database of Clarksons [2022].

The data is extracted from the Clarksons [2022] database by applying the following filters:

1. Fleet type: bulkers, chemical tankers, containerships, general cargo, LNG, LPG, MPP, Product tankers and reefers.
2. Vessel aged: 1980 till 2022.
3. DWT 2,500 till 15,000.
4. Status: 'In Service'.
5. Deployment: 20-100% (time in % last month) in UK/Continent and Mediterranean/Black sea.

B. Regulations concerning the storage of alternative fuels and energy storage systems onboard of ships

The next section describes requirements concerning the storage of alternative fuels and energy storage systems onboard of ships by class societies.

Methanol and Ethanol Fuelled vessels (Bureau Veritas NR670, Sec 3)

1.2.1 Tanks containing fuel are not to be located within accommodation spaces or machinery spaces of category A.

1.2.2 Integral fuel tanks are to be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methyl/ethyl alcohol.

1.2.4 The fuel containment system is to be abaft of the collision bulkhead and forward of the aft peak bulkhead.

1.2.5 Fuel tanks located on open decks are to be protected against mechanical damage.

1.2.7 For single fuel installations, each fuel service tank is to have a capacity of at least 8 h at maximum continuous rating of the propulsion plant and normal operating load at sea of the generator plant.

1.2.10 For single fuel installations, the fuel storage is to be divided between two or more tanks so that, in the event of any one tank becoming unavailable, the remaining tank(s) will provide sufficient fuel to enable the ship to operate within its service. These tanks are to be located in separate spaces. If those spaces are adjacent, the insulation between both spaces is to be at least A-60.

1.3.1 Independent tanks may be accepted on open decks or in a fuel storage hold space.

Gas fuelled ships; hydrogen, LNG, LPG (Bureau Veritas NR529)

5.2.1.1 The fuel tank(s) shall be located in such a way that the probability for the tank(s) to be damaged following a collision or grounding is reduced to a minimum taking into account the safe operation of the ship and other hazards that may be relevant to the ship.

5.3.1 Fuel storage tanks shall be protected against mechanical damage.

5.3.3 The fuel tank(s) shall be protected from external damage caused by collision or grounding in the following way:

.1 The fuel tanks shall be located at a minimum distance of B/5 or 11,5 m, whichever is less, measured inboard from the ship side at right angles to the centreline at the level of the summer load line draught, where B : greatest moulded breadth of the ship at or below the deepest draught (summer load line draught) (refer to SOLAS regulation II-1/2.8).

.4 In no case shall the boundary of the fuel tank be located closer to the shell plating or aft terminal of the ship than as follows:

For cargo ships:

.1 for Vc < 1000 m3: 0,8 m

.2 for 1000 m3 < Vc < 5000 m3: 0,75 + Vc * 0,2 / 4000 m

.3 for 5000 m3 < Vc < 30000 m3: 0,8 + Vc / 25000 m, and

.4 for Vc > 30000 m3: 2,0 m, Vc : Corresponds to 100% of the gross design volume of the individual fuel tank at 20 degree Celsius, including domes and appendages.

.5 The lowermost boundary of the fuel tank(s) shall be located above the minimum distance of B/15 or 2,0 m, whichever is less, measured from the moulded line of the bottom shell plating at the centre line.

.7 The fuel tank(s) shall be abaft a transverse plane at 0,08 L measured from the forward perpendicular, and abaft the collision bulkhead for cargo ships.

Fully battery powered ships (DNV 'Battery Power' Part 6, Chapter 2, Section 1)

2.2.1 EES spaces shall be positioned aft of collision bulkhead. Boundaries of EES spaces shall be part of vessels structure or enclosures with equivalent structural integrity.

2.4.1.2 Fire integrity of EES spaces shall be enclosed by A-0 fire integrity and have A-60 fire integrity towards: machinery spaces of category A as defined in SOLAS Reg. II-2/3 and enclosed cargo areas for carriage of dangerous goods.

3.2.1.1 When all the main sources of power is based on EES (electrical energy storage) only, the main sources of power shall consist of at least two independent EES systems located in two separate EES spaces.

C. Short-sea voyage data selection

Voyage distances for 3005 voyages of short-sea vessels in Europe are collected. Eurostat [Eurostat, 2022] provides data on the weight of goods transported by short-sea ships in Europe per port. Based on this distribution, a number of voyages to/from the top 35 short-sea ports in Europe (datapoints) are selected from Marine Traffic. Specific data of this method is provided in Table C.2. Figure C.1 shows the shipping routes and top 35 short-sea ports in Europe.

To guarantee the quality of the data, a number of filters are applied which are shown in Table C.1. To avoid including very short distances (voyages within ports), the data filters use a journey time of 12 hours and a minimum voyage distance of 50 nautical miles. In addition, a minimal draught of 3 metres is used as a data filter to prevent inland vessel from being included in the data set.

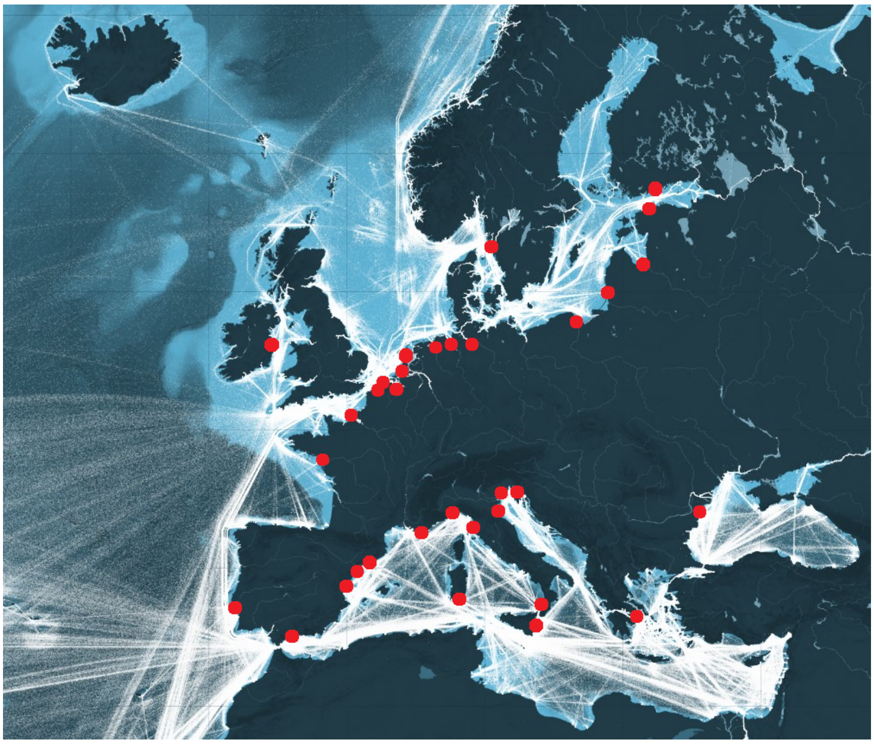


Table C.1.: Ship routes for all ships in Europe based on AIS data [Shipmap, 2022] (lighter areas indicate more traffic) with the top 35 short-sea ports in Europe indicated by red dots.

REP_MAR/TIME	Gross weight of goods transported to/from main ports (2019)	Percentage of total gt transported in EU	Percentage of top 35 ports	Number of datapoints
Rotterdam	204,210	10.48	16.46	495
Antwerpen	100,743	5.17	8.12	244
Amsterdam (Ijmuiden)	52,871	2.71	4.26	128
Trieste	46,761	2.40	3.77	113
Hamburg (Cuxhaven)	46,335	2.38	3.74	112
Algeciras	45,429	2.33	3.66	110
Marseille	45,242	2.32	3.65	110
Genova	37,972	1.95	3.06	92
Pireas	36,099	1.85	2.91	87
Gdansk	34,195	1.75	2.76	83
Göteborg	33,395	1.71	2.69	81
Valencia	30,994	1.59	2.50	75
Klaipeda	28,841	1.48	2.32	70
Constanta	28,470	1.46	2.30	69
Livorno	28,241	1.45	2.28	68
Le Havre	27,262	1.40	2.20	66
Dublin	26,012	1.33	2.10	63
Ravenna	25,170	1.29	2.03	61
Riga	25,160	1.29	2.03	61
Barcelona	23,820	1.22	1.92	58
Zeeland Seaports (Terneuzen)	23,498	1.21	1.89	57
Dunkerque	23,230	1.19	1.87	56
Sköldvik (Kilpilahti)	23,059	1.18	1.86	56
Porto Foxi	22,768	1.17	1.84	55
Wilhelmshaven	21,990	1.13	1.77	53
Venezia (Venice)	21,364	1.10	1.72	52
Zeebrugge	21,301	1.09	1.72	52
Bremerhaven	21,232	1.09	1.71	51
Nantes Saint-Nazaire	20,653	1.06	1.66	50
Tarragona	20,620	1.06	1.66	50
Ghent (Terneuzen)	19,892	1.02	1.60	48
Augusta	19,805	1.02	1.60	48
Sines	19,668	1.01	1.59	48
Gioia Tauro	18,715	0.96	1.51	45
Tallinn	15,476	0.79	1.25	37
Total	1,240,493	63.64	100.00	3005

Total SSS EU (gt)	1,949,203
Number of data points	3,005

Table C.2.: Selection of voyage data from Marine Traffic [MarineTraffic, 2022], based on transport statistics by Eurostat [Eurostat, 2022]

Filters Marine Traffic	
Draught	3-45 m
Voyage time underway	12-1000 h
Vessel type generic	Cargo, Tankers
Vessel type specific	Aggregates Carrier, Asphalt/bitumen tanker, Bulk Carrier, Cement Carrier, Chemical Tanker, Container Ship, Crude oil Tanker, General Cargo, Heavy Load Carrier, LNG Tanker, LPG Tanker, Obo Carrier, Oil Products Carrier, Oil/Chemical Tanker, Ore Carrier, Special Cargo, Special Tanker, Reefer, Tanker,
Capacity	3,000-15,000 DWT

Filters MS Excel (post-processing)	
Distance travelled	50< NM

Figure C.1.: Filters used in voyage data selection from Marine Traffic

D. Detailed data of technical and operational emission mitigation measures

	Applicability Inputs				Inputs of measure				
	Ship type and size	Applicable to ship type	Measure applicable to engine		Installation cost	OPEX	Life time	Fuel reduction	% of time measure reduces power
			Main	Aux	€	€/yr.	yrs.	%	[%]
Trim and draft optimisation	Dry cargo 3000-5000 dwt	1	1	0	25,000	0	25	1.50%	100%
	Dry cargo 5000-10000 dwt	1	1	0	25,000	0	25	1.50%	100%
	Dry cargo 10000-15000 dwt	1	1	0	25,000	0	25	1.50%	100%
	Tanker	1	1	0	25,000	0	25	1.50%	100%
	Container ship	1	1	0	25,000	0	25	1.50%	100%
Weather routing	Dry cargo 3000-5000 dwt	1	1	0	15,000	3,000	15	0.10%	100%
	Dry cargo 5000-10000 dwt	1	1	0	15,000	3,000	15	0.10%	100%
	Dry cargo 10000-15000 dwt	1	1	0	15,000	3,000	15	0.10%	100%
	Tanker	1	1	0	15,000	3,000	15	0.10%	100%
	Container ship	1	1	0	15,000	3,000	15	0.10%	100%
Just in time arrival	Dry cargo 3000-5000 dwt	1	1	0	10,000	5,000	5	2.50%	100%
	Dry cargo 5000-10000 dwt	1	1	0	10,000	5,000	5	2.50%	100%
	Dry cargo 10000-15000 dwt	1	1	0	10,000	5,000	5	2.50%	100%
	Tanker	1	1	0	10,000	5,000	5	2.50%	100%
	Container ship	1	1	0	10,000	5,000	5	2.00%	100%
Slow steaming (applies to all % speed reduction)	Dry cargo 3000-5000 dwt	1	1	0	60,000	1,000	20	varies with ship inputs	100%
	Dry cargo 5000-10000 dwt	1	1	0	80,000	1,000	20	varies with ship inputs	100%
	Dry cargo 10000-15000 dwt	1	1	0	100,000	1,000	20	varies with ship inputs	100%
	Tanker	1	1	0	100,000	1,000	20	varies with ship inputs	100%
	Container ship	1	1	0	100,000	1,000	20	varies with ship inputs	100%

Table D.1.: Detailed input assumptions for operational carbon reducing measures

Measure	Ship type and size	Applicable to ship type (Applicability Inputs)	Measure applicable to engine: Main	Measure applicable to engine: Aux	Installation cost (Inputs of measure)	OPEX	Life time	Fuel reduction	% of time measure reduces power
					€	€/yr.	yrs.	%	[%]
Efficient rudder	Dry cargo 3000-5000 dwt	1	1	0	650,000	0	20	3.70%	100%
	Dry cargo 5000-10000 dwt	1	1	0	650,000	0	20	3.70%	100%
	Dry cargo 10000-15000 dwt	1	1	0	650,000	0	20	3.70%	100%
	Tanker	1	1	0	650,000	0	20	3.70%	100%
	Container ship	1	1	0	650,000	0	20	3.70%	100%
Hull coating	Dry cargo 3000-5000 dwt	1	1	0	22,000	0	5	2.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	30,000	0	5	2.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	38,000	0	5	2.00%	100%
	Tanker	1	1	0	36,000	0	5	2.00%	100%
	Container ship	1	1	0	82,000	0	5	1.50%	100%
Air lubrication	Dry cargo 3000-5000 dwt	1	1	0	130,000	10,000	25	7.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	380,000	10,000	25	7.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	900,000	10,000	25	7.00%	100%
	Tanker	1	1	0	320,000	10,000	25	7.00%	100%
	Container ship	1	1	0	510,000	10,000	25	3.00%	100%
High efficiency propeller	Dry cargo 3000-5000 dwt	1	1	0	400,000	0	20	2.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	400,000	0	20	2.50%	100%
	Dry cargo 10000-15000 dwt	1	1	0	400,000	0	20	3.00%	100%
	Tanker	1	1	0	400,000	0	20	3.00%	100%
	Container ship	1	1	0	400,000	0	20	3.00%	100%
Wake-equalizing duct	Dry cargo 3000-5000 dwt	1	1	0	525,000	0	20	2.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	525,000	0	20	2.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	525,000	0	20	2.00%	100%
	Tanker	1	1	0	525,000	0	20	2.00%	100%
	Container ship	1	1	0	525,000	0	15	2.00%	100%
Pre and post-swirl devices	Dry cargo 3000-5000 dwt	1	1	0	100,000	0	20	2.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	125,000	0	20	2.25%	100%
	Dry cargo 10000-15000 dwt	1	1	0	150,000	0	20	2.50%	100%
	Tanker	1	1	0	125,000	0	20	2.25%	100%
	Container ship	1	1	0	125,000	0	20	3.00%	100%
Contra rotating propeller	Dry cargo 3000-5000 dwt	1	1	0	650,000	20,000	20	7.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	700,000	20,000	20	7.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	785,000	20,000	20	7.00%	100%
	Tanker	1	1	0	690,000	20,000	20	7.00%	100%
	Container ship	1	1	0	780,000	20,000	20	7.00%	100%
Fixed wings or sails	Dry cargo 3000-5000 dwt	1	1	0	300,000	30,000	15	11.40%	100%
	Dry cargo 5000-10000 dwt	1	1	0	500,000	50,000	15	6.40%	100%
	Dry cargo 10000-15000 dwt	1	1	0	500,000	50,000	15	3.40%	100%
	Tanker	1	1	0	500,000	50,000	15	7.60%	100%
	Container ship	0	0	0	0	0	0	0.00%	0%

Measure	Ship type and size	Applicable to ship type	Measure applicable to engine: Main	Measure applicable to engine: Aux	Installation cost	OPEX	Life time	carbon reduction	% of time measure reduces power	Fuel reduction
					€	€/yr.	yrs.	%	[%]	%
Carbon capture and storage	Dry cargo 3000-5000 dwt	1	1	1	950,000	8,000	15	25.00%	100%	0.00%
	Dry cargo 5000-10000 dwt	1	1	1	950,000	8,000	15	25.00%	100%	0.00%
	Dry cargo 10000-15000 dwt	1	1	1	950,000	8,000	15	25.00%	100%	0.00%
	Tanker	1	1	1	950,000	8,000	15	25.00%	100%	0.00%
	Container ship	1	1	1	950,000	8,000	15	25.00%	100%	0.00%

Measure	Ship type and size	Applicable to ship type	Measure applicable to engine: Main	Measure applicable to engine: Aux	% income increase vs capacity increase	Installation cost	OPEX	Life time	Fuel reduction	% of time measure reduces power
						€	€/yr.	yrs.	%	[%]
Increase in capacity 10%	Dry cargo 3000-5000 dwt	1	1	0	70%	530,000	1,000	20	0.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	70%	1,100,000	1,000	20	0.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	70%	1,500,000	1,000	20	0.00%	100%
	Tanker	0	0	0	70%	1,500,000	1,000	20	0.00%	100%
	Container ship	1	1	0	70%	1,500,000	1,000	20	0.00%	100%
Increase in capacity 20%	Dry cargo 3000-5000 dwt	1	1	0	0.00%	1,060,000	1,000	20	0.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	1.50%	2,200,000	1,000	20	0.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	1.30%	3,000,000	1,000	20	0.00%	100%
	Tanker	0	0	0	0.00%	3,000,000	1,000	20	0.00%	100%
	Container ship	1	1	0	0.00%	3,000,000	1,000	20	0.00%	100%
Increase in capacity 30%	Dry cargo 3000-5000 dwt	1	1	0	0.00%	1,590,000	1,000	20	0.00%	100%
	Dry cargo 5000-10000 dwt	1	1	0	2.20%	3,300,000	1,000	20	0.00%	100%
	Dry cargo 10000-15000 dwt	1	1	0	2.00%	4,500,000	1,000	20	0.00%	100%
	Tanker	0	0	0	0.00%	4,500,000	1,000	20	0.00%	100%
	Container ship	1	1	0	0.00%	4,500,000	1,000	20	0.00%	100%

Table D.2.: Detailed input assumptions for technical carbon reducing measures

Fuel reduction and cost estimations per measure

Efficient rudder: fuel saving 3,7% for all vessels and types [Wartsila, nd] and a cost EUR 650.000 [GloMEEP, ndf].

Hull coating: fuel reduction and installation cost depend on vessel size and type and vary between 1,5-2,0% and EUR 22.000-82.000 [GloMEEP, nda].

Air cavity lubrication: fuel reduction depend on ship type and size and vary between 3,0-7,0%. The installations cost varies between EUR 130.000-900.000 and OPEX EUR 10.000 and constant for all ships.

High efficiency propeller: suitable for retrofitting in combination with slowsteaming. Cost of installation of a new propeller and CFD analyses is estimated as EUR 400.000 [Solutions, nd] [GloMEEP, nde]. The fuel reduction varies between 2,0-3,0% dependent on vessel type and size.

Wake equalizing duct: installation cost of EUR 525.000 regardless of ship type and size. The fuel reduction potential is estimated as 2% for all vessel types and sizes Xing et al. [2020].

Pre and post-swirl devices: Installation cost vary between EUR 100.000-150.000 [GloMEEP, ndf]. Fuel reduction is between 2-3% [Mizzi, 2016] [GloMEEP, ndf].

Contra rotating propeller: Installation cost varies between EUR 650.000-785.000. The fuel reduction potential is constant for all vessels, at 7% [IMO, nd]. The OPEX for this system is estimated as EUR 20.000 for all ships [IMO, nd].

Carbon capture and storage device: Cost of the systems is EUR 950,000 and is fixed for all vessel types and sizes [Nesec, 2023]. The OPEX are estimated at EUR 8,000 per year [Nesec, 2023]. This measure allows the ship to use cheaper HFO as it reduces the SOx emitted, making it compliant to sail in ECAs. Therefore fuel cost reduction due to the spread in HFO and LSFO prices is included in the cost-benefit analyses of this emission mitigation measure. This spread is assumed to have a value of €207/t, regardless of the price level of HFO and LSFO. The spread value is based on the historical average spread between HFO and LSFO.

The measure is estimated to have no influence on the amount fuel consumption, although fuel consumption may increase due to the carbon capture systems energy demand and its effect on the flow of exhaust gasses. Carbon capture and storage systems have the potential to reduce carbon emissions to zero [Nesec, 2023], however this report uses a conservative estimate of 25% reduction in carbon emissions.

Fixed wings or sails: Installation cost and OPEX vary between EUR 300.000-500.000 and EUR 30.000-50.000 dependent on ship type and size [IMO, nd]. The lifetime of the systems is estimated as 15 years and the fuel reduction potential varies between 3.4-11.4% [IMO, nd].

Slow steaming (engine de-rating): The cost of ship and engine modifications are estimated to be €60,000-80,000 dependent on ship type [Nesec, 2023]. This value does not depend on the degree of speed reduction. The operational expenses of slow-steaming are not mentioned in literature, to include the OPEX a rough value of €1000 per year is assumed [Nesec, 2023].

Capacity increase: The system cost is estimated based on the DWT increase and the value of new-build vessels of similar type and size [Nesec, 2023]. This is estimation method is chosen as value are not publicly known and this methods is conservative in its cost estimation.

Trim and draft optimisation: the system cost are estimated as €25,000, constant for all vessel types and sizes[IMO, nd]. The fuel reduction percentage is assumed constant for all vessel types and sizes at 1.5% [IMO, nd].

Weather routing: the system cost and OPEX are estimated as €15,000 and €3,000 per year, constant for all vessel types and sizes[IMO, nd]. The fuel reduction percentage is assumed constant for all vessel types and sizes at 0.1% [IMO, nd].

E. Detailed data of marine fuels used in the Comparison Tool

Fuel type	% pilot fuel	η_e	average SFC [g/kWh]	Energy density [GJ/t]	Energy density [GJ/m3]	Cf [tCO2/tfuel]
Diesel/Gas oil	0.00	0.43	194.70	43	35.7	3.206
Light Fuel Oil (LFO)	0.00	0.43	194.70	43	35.7	3.151
Heavy Fuel Oil (HFO)	0.00	0.43	209.30	40		3.114
Liquefied Petroleum Gas (LPG) Propane	3.00	0.43	168.79	49.6	26.7	3
Liquefied Petroleum Gas (LPG) Butane	3.00	0.43	170.51	49.1	26.7	3.03
Liquefied Natural Gas (LNG)	2.00	0.43	156.20	53.6	21.2	2.75
Methanol	5.00	0.43	424.98	19.7	14.9	1.373
Ethanol	15.00	0.31	414.75	28	21	1.913
Fully electric (battery powered)	0.00	0.95	-	battery storage: 0.25 [kWh/kg]	battery storage 700 [kWh/m3]	0
Hydrogen	0.00	0.25	120.00	120	8.5	0

Table E.1.: Overview of the parameters for the marine fuels used in the Comparison Tool

	Applicability Inputs				Inputs of measure						
	Ship type and size	Applicable to ship type	Measure applicable to engine		Installation cost engine and fuel tank retrofit	Fuel price	OPEX	Life time	% (diesel) pilot fuel	Max voyage distance	% of time measure reduces power
			Main	Aux		€/t	€/yr.	yrs.	%	[nm]	[%]
Methanol	Dry cargo 3000-5000 dwt	1	1	0	270 €/kWh	321	1,000	20	5.00%	1200	100%
	Dry cargo 5000-10000 dwt	1	1	0		321	1,000	20	5.00%	1500	100%
	Dry cargo 10000-15000 dwt	1	1	0		321	1,000	20	5.00%	2000	100%
	Tanker	1	1	0		321	1,000	20	5.00%	1500	100%
	Container ship	1	1	0		321	1,000	20	5.00%	1000	100%
LNG	Dry cargo 3000-5000 dwt	1	1	0	€ 1,000,000	712	1,000	20	2.00%	1200	100%
	Dry cargo 5000-10000 dwt	1	1	0	€ 1,200,000	712	1,000	20	2.00%	1500	100%
	Dry cargo 10000-15000 dwt	1	1	0	€ 1,500,000	712	1,000	20	2.00%	2000	100%
	Tanker	1	1	0	€ 1,500,000	712	1,000	20	2.00%	1500	100%
	Container ship	1	1	0	€ 1,500,000	712	1,000	20	2.00%	1000	100%
LPG	Dry cargo 3000-5000 dwt	1	1	0	€ 1,000,000	496	1,000	20	3.00%	1200	100%
	Dry cargo 5000-10000 dwt	1	1	0	€ 1,200,000	496	1,000	20	3.00%	1500	100%
	Dry cargo 10000-15000 dwt	1	1	0	€ 1,500,000	496	1,000	20	3.00%	2000	100%
	Tanker	1	1	0	€ 1,500,000	496	1,000	20	3.00%	1500	100%
	Container ship	1	1	0	€ 1,500,000	496	1,000	20	3.00%	1000	100%
Hydrogen	Dry cargo 3000-5000 dwt	1	1	0	Energy system: 2100 EUR/kW Storage: 1500 EUR/kg	2,020	1,000	20	0.00%	1200	100%
	Dry cargo 5000-10000 dwt	1	1	0		2,020	1,000	20	0.00%	1500	100%
	Dry cargo 10000-15000 dwt	1	1	0		2,020	1,000	20	0.00%	2000	100%
	Tanker	1	1	0		2,020	1,000	20	0.00%	1500	100%
	Container ship	1	1	0		2,020	1,000	20	0.00%	1000	100%
Fully electric	Dry cargo 3000-5000 dwt	1	1	0	Motor: 500 EUR/kW Batteries: 227 EUR/kWh	0,091 €/kWh	1,000	12	0.00%	1200	100%
	Dry cargo 5000-10000 dwt	1	1	0		0,091 €/kWh	1,000	12	0.00%	1500	100%
	Dry cargo 10000-15000 dwt	1	1	0		0,091 €/kWh	1,000	12	0.00%	2000	100%
	Tanker	1	1	0		0,091 €/kWh	1,000	12	0.00%	1500	100%
	Container ship	1	1	0		0,091 €/kWh	1,000	12	0.00%	1000	100%
Ethanol	Dry cargo 3000-5000 dwt	1	1	0	810,000	796	1,000	20	15.00%	1200	100%
	Dry cargo 5000-10000 dwt	1	1	0	810,000	796	1,000	20	15.00%	1500	100%
	Dry cargo 10000-15000 dwt	1	1	0	810,000	796	1,000	20	15.00%	2000	100%
	Tanker	1	1	0	810,000	796	1,000	20	15.00%	1500	100%
	Container ship	1	1	0	810,000	796	1,000	20	15.00%	1000	100%

Table E.2.: Overview of the parameters for the marine fuels used in the Comparison Tool

The following text specifies all fuel specific data sources for the data in Tables E.1 and E.2. General assumptions are that OPEX is 1000 per year for all marine propulsion systems. Furthermore, the lifetime of all systems except battery storage systems are assumed to have a lifetime of 20 years.

Methanol

Methanol is assumed to require 5% diesel pilot fuel (95% methanol and 5% diesel) [MAN, 2021]. The effective efficiency of methanol is estimated as $\eta_e = 0.43$ [Bozzano, 2016], similar to the effective efficiency of diesel combustion engines. The combined cost for engine and fuel tank conversion is estimated as €270/kW engine power[Energy, 2015]. The fuel price is estimated at €321/t based on the historical Methanex European Posted Contract Price [Methanex, 2023].

Ethanol

Ethanol is assumed to require 15% of diesel pilot fuel (85% ethanol and 15% diesel) [Graham-Rowearchive, 2009]. The effective efficiency of ethanol is estimated as $\eta_e = 0.31$ [Graham-Rowearchive, 2009], about 30% less effective than diesel combustion engines. The combined cost for engine and fuel tank conversion is assumed to be similar to methanol, €270/kW engine power [Energy, 2015]. The fuel price is estimated at €796/t based on the historical price [ChemAnalyst, 2023] [TE, 2023b].

LNG
LNG combustion engines are assumed to require a minimal of 2% of diesel pilot fuel (98% LNG and 2% diesel) [EIBIP, 2018]. The effective efficiency of LNG is estimated as $\eta_e = 0.43$ [wartsila, 2013], similar to the effective efficiency of diesel combustion engines. The cost for engine retrofit to LNG is estimated to cost between $300,000–$1.5 million. The fuel price is estimated at €712/t based on the historical price trends [RB, 2023].

LPG
LPG combustion engines are assumed to require a minimal of 3% of diesel pilot fuel (97% LPG and 3% diesel) [MAN, 2018]. The effective efficiencies of LPG combustion engines are not publicly available, therefore the same effective efficiency as LNG combustion engines are used as an estimate ($\eta_e = 0.43$). No data on engine and fuel tank conversion cost are available in literature, therefore the cost are estimate to be similar to LNG conversion. The fuel is estimated at €496/t based on the historical prices [ICIS, 2020] [TE, nd].

Hydrogen
Hydrogen does not need any pilot fuel. The effective efficiency of energy generation using hydrogen are estimated as $\eta_e = 0.25$ [Hosseini, 2019], about 60% less effective than diesel combustion engines. The cost for hydrogen fuel cell system is estimated to be 2100 EUR/kW and cost for storage tank and systems 1500 EUR/kg [Fredrik, 2022]. The fuel price is estimated at €2020/t based on the historical prices and price expectations [IEA, 2019] [Vickers et al., 2020].

Fully electric (battery powered)
The efficiency of electrical marine motors is estimated as $\eta_e = 0.95$ [Torstein, 2017] [Zaccone, 2021]. Gravimetric and volumetric energy storage densities of lion batteries are estimated as 0,25 [kWh/kg] and 700 [kWh/m3] [Percic et al., 2022]. The electricity price is estimated as 0.091 [euro/kWh], which is the historical average electricity price for non-household consumers in the Europe [Eurostat, 2023]. The cost for the motor is estimated at 500 EUR/kW [EC, 2018] and battery storage at 227 EUR/kWh [BV, 2021]. The lifetime of lion-ion batteries are approximate 12 years [Hoedemaker, 2017], therefore the cost calculation is performed for a 12 year lifespan.

F. Cashflow example calculation

Dry cargo 3000-5000 dwt												
Year	0	1	2	3	4	5		16	17	18	19	20
Asset value	**100,000**	**93,000**	**86,000**	**79,000**	**72,000**	**65,000**	...	**-12,000**	**-19,000**	**-26,000**	**-33,000**	**-40,000**
Depreciation	0	-7,000	-7,000	-7,000	-7,000	-7,000		-7,000	-7,000	-7,000	-7,000	-7,000
Loan value	**100,000**	**95,000**	**90,000**	**85,000**	**80,000**	**75,000**		**20,000**	**15,000**	**10,000**	**5,000**	**0**
Repayment investment	0	-5,000	-5,000	-5,000	-5,000	-5,000		-5,000	-5,000	-5,000	-5,000	-5,000
WACC	0	-6,650	-6,300	-5,950	-5,600	-5,250		-1,400	-1,050	-700	-350	0
OPEX	0	0	0	0	0	0		0	0	0	0	0
Fuel cost reduction	0	17,640	18,032	18,424	18,816	19,208		19,600	19,600	19,600	19,600	19,600
EU ETS cost reduction	0	0	2,329	4,249	6,316	6,563		6,809	6,809	6,809	6,809	6,809
Cashflow	0	5,990	9,061	11,723	14,532	15,521		20,009	20,359	20,709	21,059	21,409
Present value of cashflow	0	5,760	8,378	10,422	12,422	12,757		10,683	10,452	10,223	9,995	9,771
Cumulative cashflows (EUR)	**0**	**5,760**	**14,137**	**24,559**	**36,981**	**49,738**		**180,226**	**190,678**	**200,900**	**210,896**	**220,666**

Figure F.1.: Cashflow example calculation for technical measure in the Comparison Tool: pre and post-swirl device for dry cargo vessel in capacity range 3,000-5,000 DWT with a life time of 20 years.

G. Data inputs for the short-sea reference vessels

	Reference vessel	Dry Cargo Vessels (DCV)			TV	CV
Inputs for Holtrop-Mennen	Cb	0.75	0.75	0.75	0.8	0.67
	Cwp	0.83	0.83	0.83	0.87	0.78
	Cm	0.992	0.992	0.992	0.996	0.980
	B [m]	13	16	20	17	22
	T [m]	5	7	8	6.5	7.5
	LOA [m]	90	120	145	105	140
Technical inputs	Capacity [dwt]	3850	8000	14500	7050	9300
	Capacity [gt]	2550	5750	9850	4350	7950
	Speed - speed at 100% MCR [kn]	12	13.5	15	12	17
	Speed - speed at 75% MCR (Vref) [kn]	10.9	12.3	13.6	10.9	15.4
	Ice-class	n/a	n/a	n/a	n/a	n/a
	Tank capacity (Tankers only) [m3]	n/a	n/a	n/a	7750	n/a
Main engine inputs	Propulsion type	Conv.	Conv.	Conv.	Conv.	Conv.
	Is the engine derated	no	no	no	no	no
	Maximum Continuous Rating (MCR)	1100	3000	6000	2650	6000
	Specific fuel consumption – at 75% MCR	Calculated based on engine type and MCR				
	Engine type	MSDE	MSDE	MSDE	MSDE	MSDE
	Fuel type 1	D/G oil	D/G oil	D/G oil	D/G oil	D/G oil
	Fuel type 2	n/a	n/a	n/a	n/a	n/a
	Annual fuel consumption (fuel type 1)	1400	1350	1300	1400	2400
	Annual fuel consumption (fuel type 2)	n/a	n/a	n/a	n/a	n/a
Operational inputs	% voyages sailed between EU ports	53	41	26	38	39
	% voyages sailed between EU and non-EU ports	41	53	69	25	53
	% voyages sailed between non-EU ports	6	6	5	13	8
	Days of sailing per year	180	160	145	140	153
	Days in port per year	185	205	220	225	212
	Max distance between refueling to cover 90% of SSS routes	1200	1500	2000	1500	1000
	Annual distance travelled [nm]	38000	34500	28000	25250	34000
Auxiliary engine inputs	Specific fuel consumption – at 50% MCR	215	215	215	215	215
	Fuel type	D/G oil	D/G oil	D/G oil	D/G oil	D/G oil
	Annual fuel consumption	130	195	230	255	335

Table G.1.: Data inputs in the Comparison Tool for the short-sea reference vessels

H. Model Verification

Verification item	Technique(s) used	Description	Results / Conclusion	Confidence in results
EU ETS calculation	Extreme condition test	EU ETS price set to zero	Performs as expected	High
EU ETS calculation	Extreme condition test	% voyages sailed between EU and non-EU ports' and '% voyages sailed between EU ports ' set to zero	Performs as expected	High
EEXI & Cost calculation	Extreme condition test	'Days of sailing' set to zero	Performs as expected	High
CII calculation	Extreme condition test	Speed - speed at 75% MCR (Vref)' set to zero	Performs as expected	High
Slow steaming & ΔEEXI calculation	Extreme condition test	Maximum Continuous Rating (MCR)' set to zero	Performs as expected	High
Cost calculation	Extreme condition test	Fuel price input set to zero	Performs as expected	High
Slow steaming & capacity lost/gained income calculation	Extreme condition test	TCE input price set to zero	Performs as expected	High
Cost calculation technical measures	Extreme condition test	Fuel reduction set to zero	Performs as expected	High
Cost calculation	Extreme condition test	Installation cost set to zero	Performs as expected	High
Cost calculation slow steaming	Data relation correctness	Analysing trend of cost/tCO2 versus % speed reduction	Performs as expected	High
EU ETS calculation	Data relation correctness	Double '% voyages sailed between EU ports' and '% voyages sailed between EU and non-EU ports' should result in double EU ETS cost	Performs as expected	High
EEXI calculation	Data relation correctness	Double 'Speed - speed at 75% MCR (Vref)' should result in half EEXI	Performs as expected	High
ΔEEXI calculation	Data relation correctness	Double 'Fuel reduction' of measure should result in double ΔEEXI	Performs as expected	High
CII calculation	Data relation correctness	Double annual FC should result in double CII value	Performs as expected	High
Cost calculation capacity increase	Data relation correctness	Analysing trend of cost/tCO2 versus % capacity increase	Performs as expected	High
CO2 emission calculation	Structured walkthrough	Manual calculation	Performs as expected	High
EU ETS annual cost calculation	Structured walkthrough	Manual calculation	Performs as expected	High
CII calculation	Structured walkthrough	Manual calculation	Performs as expected	High
EEXI calculation	Structured walkthrough	Manual calculation	Performs as expected	High

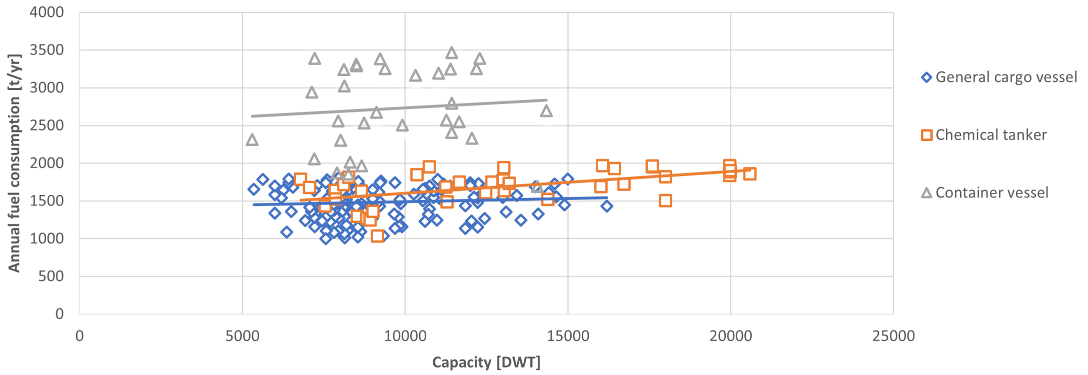
Table H.1.: Evaluation of (conceptual) model verification

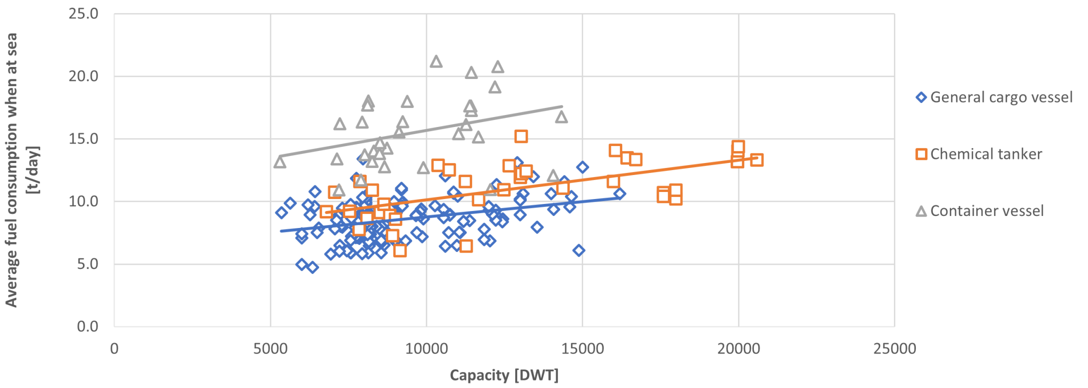
I. Model Validation

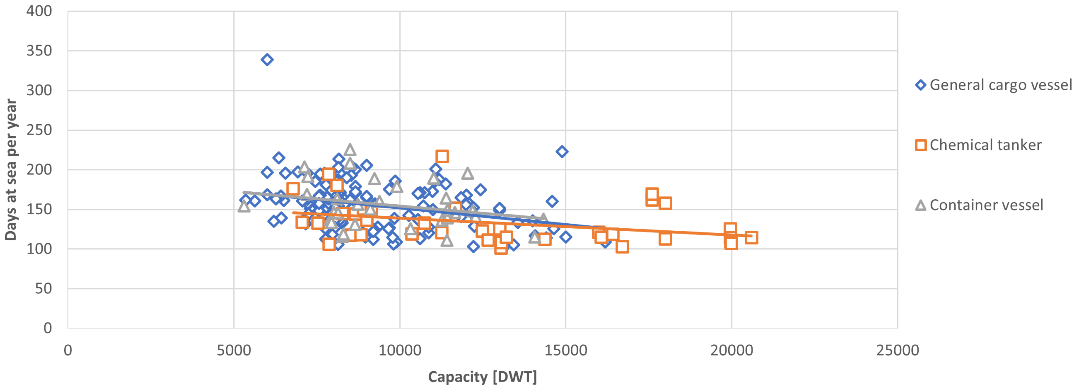
Validation item	Technique(s) used	Description	Results / Conclusion	Confidence in results
CII calculation	Results comparison with other computational tools	CII value compared to Lloyd's Register CII Calculator	Performs as expected	High
EEXI calculation	Results comparison with other computational tools	EEXI value compared to Lloyd's Register EEXI Calculator	Performs as expected	High
Financial input data for emission mitigation measures	Face validity	Questionary send to NESEC team to validate and comment on financial inputs of measures	Values considered reasonable	Medium
Technical and financial input data for emission mitigation measures	Literature data review	Data inputs of measures based on multiple sources to examine validity	Values considered reasonable	Medium

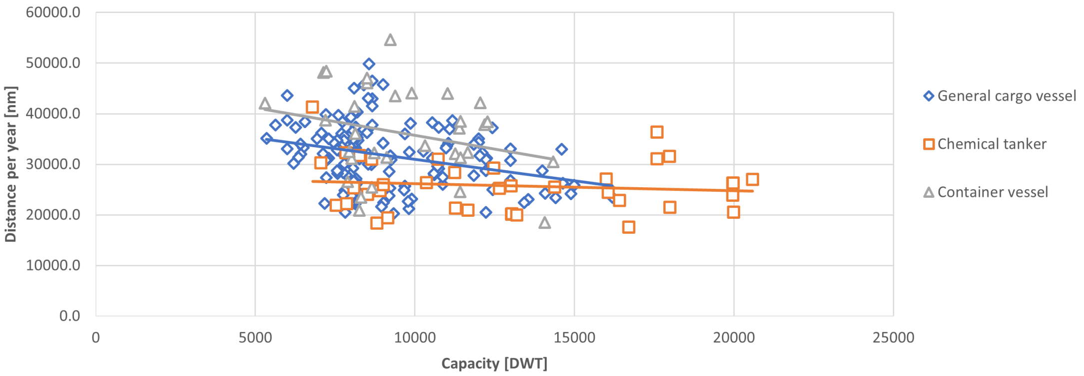
Table I.1.: Evaluation of (conceptual) model validation

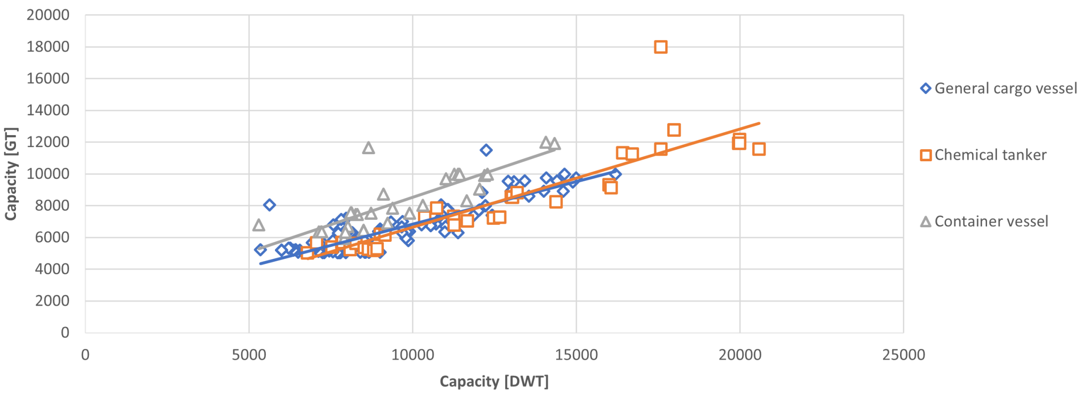
J. Operational data of short-sea vessel from THETIS database

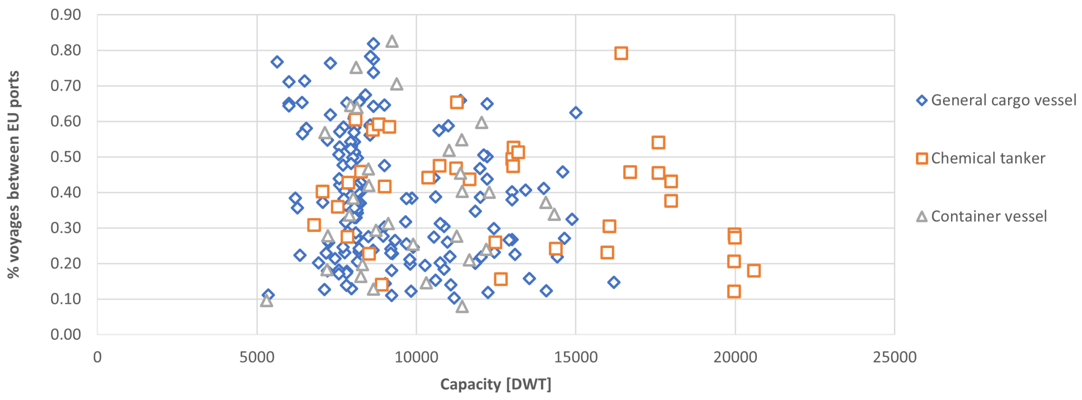


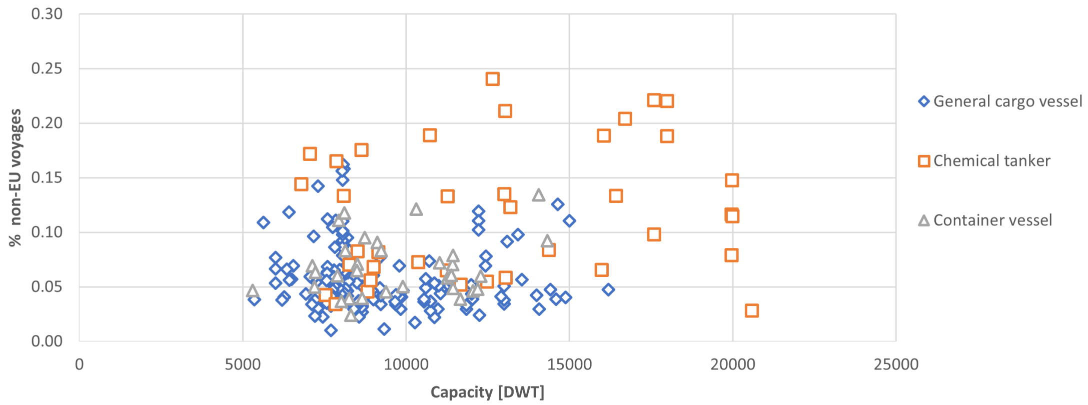


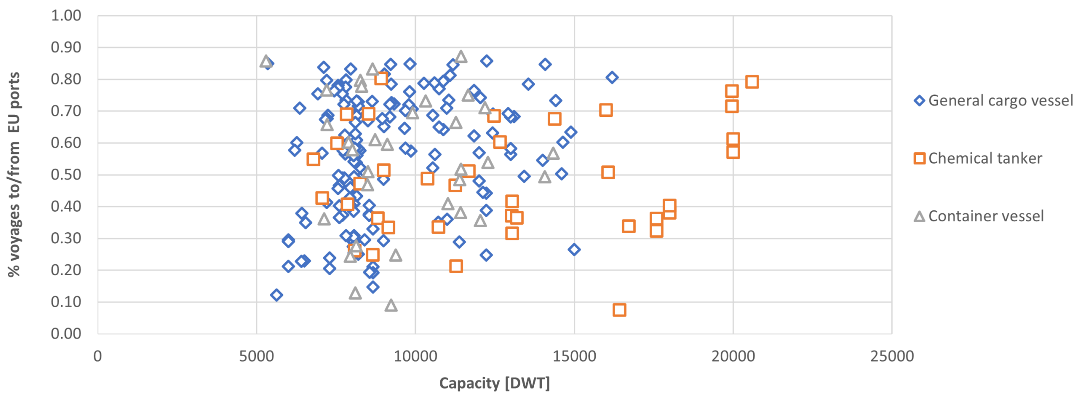

Days at sea per year
Capacity [DWT]
General cargo vessel
Chemical tanker
Container vessel
0
50
100
150
200
250
300
350
400
0
5000
10000
15000
20000
25000


Distance per year [nm]
Capacity [DWT]
General cargo vessel
Chemical tanker
Container vessel
0.0
10000.0
20000.0
30000.0
40000.0
50000.0
60000.0
0
5000
10000
15000
20000
25000


Capacity [GT]
Capacity [DWT]
General cargo vessel
Chemical tanker
Container vessel
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
0
5000
10000
15000
20000
25000


% voyages between EU ports
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
5000
10000
15000
20000
25000
Capacity [DWT]
General cargo vessel
Chemical tanker
Container vessel


% non-EU voyages
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5000
10000
15000
20000
25000
Capacity [DWT]
General cargo vessel
Chemical tanker
Container vessel


% voyages to/from EU ports
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
5000
10000
15000
20000
25000
Capacity [DWT]
General cargo vessel
Chemical tanker
Container vessel

K. Feasibility requirements for technical emission mitigation measures

Emission mitigation measure		Requirements
Ship resistance	bulbous bow	N/A
	fficient rudder	N/A
	Extra midship-section	Space requirements: • Maximum allowable ships length dependent on ports of call.
	Hull coating	N/A
	\ir lubrication	N/A
Propulsion efficiency	high-efficiency propeller	N/A
	wake-equalizing ducts	N/A
	Pre-swirl and post-swirl devices	N/A
	Contra Rotating Propeller	N/A
Power plant	Flexible power systems	Space requirements: • Additional space in the engine room dependent on size of PTI/PTO, generator sets, gearbox, control panels and switchboards. (4)
	Carbon capture and storage	Space requirements: • Carbon capture device has an approximated size as a 40ft container. (1) • Carbon storage tanks are placed in 1 or 2 20ft cotainers. (1) Location requirements: • The carbon capture device should be close to the exhaust funnel. (1) • The carbon storage (container) should be removable and easily accessible
	Waste Heat Recovery	Main engine requirements: • Only effective on large ships with main engine power higher than 20,000 kW (5) Space requirements: • Additional space in the engine room dependent on size of boiler, generator, turbine, PTI/PTO. (6)
	Efficient auxiliary systems	N/A
Alternative power sources	'lettner rotors	Space requirements: • Size approximately the same as a 40ft container (2) (3) Location requirements: • The location should be chosen so that the wind can flow freely past the device.
	Wing sails	
	Kites	Voyage requirements: • Kites are more favourable on long international trades where larger ships tend to trade. (7) Space requirements: • Attachement to the ship at the bow of the vessel. 8) Location requirements: • Size approximately the same as a 20ft container. (8) TRL requirements: • Systems have a low TRL and are not ready for large scale implementation. (5)

Table K.1.: Requirements for technical emission mitigation measures for them to be technically feasible for short-sea vessels. Data sources: (1) ValueMaritime [ndb] (2) ECONOWIND [nd] (3) Ecoflettner [nd] (4) BergerMaritiem [nd] (5) ICCT [2011] (6) Olaniyi and Prause [2020] (7) GloMEEP [ndc] (8) Airseas [nd]

L. Technology readiness level of marine fuel alternatives

The technology readiness levels (TRL) for fuel production, and fuel storage, engine and process systems are compared in Table L.1. The TRL is defined on a scale 1 to 9, in which level 1 stands for 'observing basic principles' and level 9 represents a fully proven and operational system. The definition of all the TRL's are presented in Appendix D. Table L.1 shows that availability of methanol and ethanol is limited. Furthermore, the technology for fuel storage, engine and process systems for methanol, ethanol and hydrogen are not ready for full scale implementation on ships.

Fuel	Fuel production (1)		Fuel storage, engine and process systems (2)
	TRL 2019	TRL 2030	TRL 2019
Diesel/Gas oil	10	10	10
Light Fuel Oil (LFO)	10	10	10
Heavy Fuel Oil (HFO)	10	10	10
Liquefied Petroleum Gas (LPG) Propane	10	10	10
Liquefied Petroleum Gas (LPG) Butane	10	10	10
Liquefied Natural Gas (LNG)	10	10	10
Methanol	5-9	6-9	3-5
Ethanol	8-9	9-10	3-5
Battery	n/a	n/a	10
Hydrogen	10	10	0-3

Table L.1.: Technology readiness level of (grey) alternative and fossil fuels. (Data sources: (1) Verbeek et al. [2019], (2) DNV [2019a])

M. Space and location requirements of fuels alternatives

Alternative fuel	Space requirements	Location requirements
Liquefied Petroleum Gas (LPG) Propane/Butane	• 18 GJ/m3 (including storage systems) (4)	The fuel tank(s) shall be protected from external damage caused by collision or grounding in the following way: • location at a minimum distance of B/5 or 11,5 m from the ship side (2) • max distance to shell plating for Vc < 1000 m3: 0,8 m or 0,8 + Vc / 25000 m (for 1000 m3 < Vc < 5000 m3) (2) • Max distance to bottom shell plating B/15 or 2,0 m (2) • Tank location abaft a transverse plane at 0,08 L measured from the forward perpendicular, and abaft the collision bulkhead. (2)
Liquefied Natural Gas (LNG)	• 13 GJ/m3 (including storage systems) (4)	
Hydrogen	• Liquid hydrogen: 5.5 GJ/m3 (including storage systems) (4) • Compressed (gas) hydrogen: 3.2 GJ/m3 (including storage systems) (4)	
Methanol	• 14.5 GJ/m3 (including storage systems) (4)	• Tanks should be surrounded by protective cofferdams, except for shell plating below the waterline. (1) • Tank should be located abaft of the collision bulkhead and forward of the aft peak bulkhead. (1) • Fuel tanks located on open decks are to be protected against mechanical damage (1)
Ethanol	• 21.5 GJ/m3 (including storage systems) (4)	
Battery	• 2.52 GJ/m3 (including storage systems) (4) • When main sources of power, at least two independent EES systems are required located in two separate spaces. (3)	• Location aft of collision bulkhead. (3)

Table M.1.: Requirements for alternative fuels for them to be technically feasible for short-sea vessels. (Data sources: (1) BV [2022] (2) BV [nd] (3) DNV [nda] (4) DNV [2019a])

N. Historical prices

Time-charter rates reference vessels

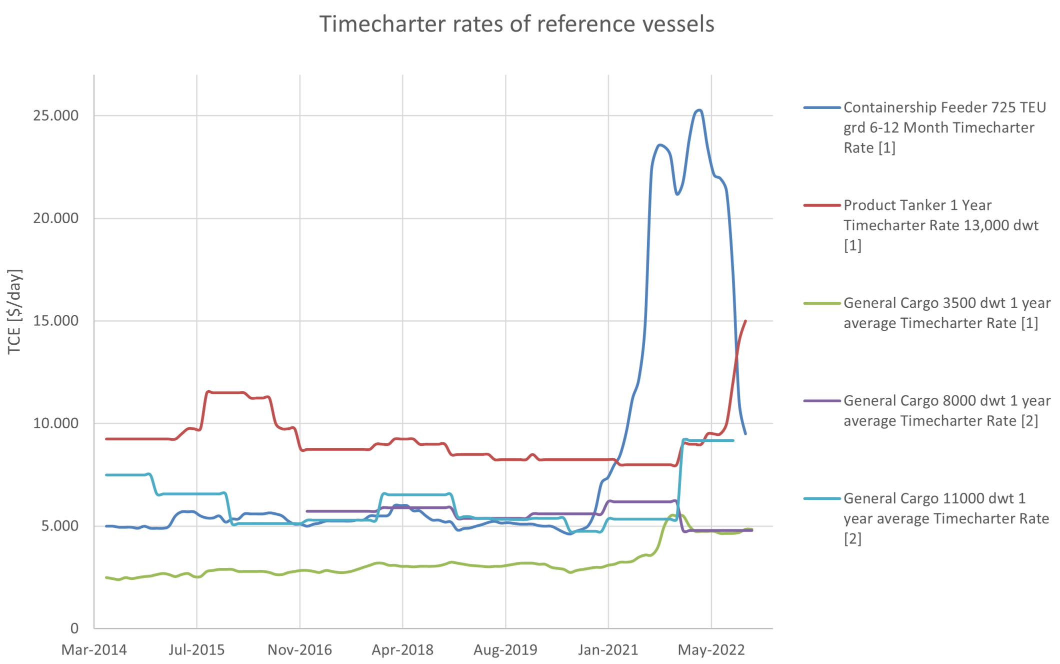


Figure N.1.: Historical time-charter rates of the five reference vessels (Data source: [1] [Clarksons, 2022], [2] [Nesec, 2022])

Figure N.1 presents the historical time-charter rates for the five reference short-sea vessels. This data is used as input for the TCE price scenarios. In which the price trajectories start at the actual price and move to a long-term average price in a five-year period for a low, base and high case scenario.

Historical prices ULSFO

Historical prices for ULSFO are based on data from Statista [2023], which present monthly averaged prices based on prices from the top 20 ports worldwide.

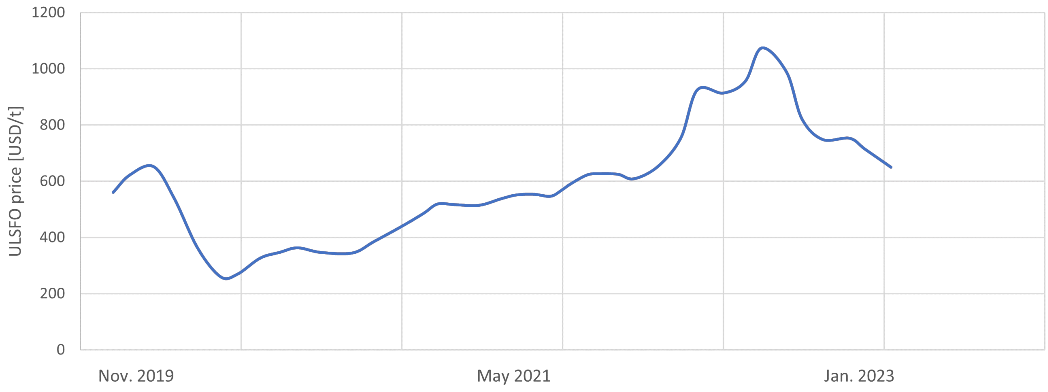


Figure N.2.: Historical prices ULSFO (Data source: [Statista, 2023])

Historical prices EU ETS Allowances

Historical prices for EU ETS Allowances are based on data from Statista [2023] and are presented in Figure N.3.

Figure N.3.: Historical prices EU ETS Allowances (Data source: [Economics, 2023])

O. Interaction between fuel price, EU ETS price and TCE price

The relationships between TCE, fuel price, EU ETS are presented for a set of increases/decreases in price:

When TCE are high, there is an incentive to install technical measure and not to slow steam as opportunity cost are high.

When TCE are low, there is an incentive to slow steam as opportunity cost are low.

When fuel prices are high, there are incentives to install measure, slow steam or change fuel strategy.

When fuel prices are low, incentives are reduced to install measures, slow steam or change fuel strategy.

When EU ETS are high, there is an incentive to lower carbon emissions by all measures/strategies.

When EU ETS are low, incentive for all carbon reducing measures/strategies are reduced.

Furthermore, Figure O.1 present the relation between TCE rates and fuel and EU ETS cost. When fuel prices are high, TCE are reduced and visa versa. When EU ETS are high, TCE are reduced and visa versa. This illustrates that the low case in which fuel prices are low and TCE are low, is extreme. As TCE rates are expected to rise due to lower fuel cost when fuel price are low.

Gross result	= €/t * days sailing * dwt capacity
- Other expenses	= harbour cost, pilot cost, commission etc.
- Fuel cost	
- EU ETS cost	
Nett result	= TCE * days sailing

Figure O.1.: Method of calculation of the TCE prices for ships

P. Cost effectiveness of carbon reducing measures

General cargo 3850 DWT

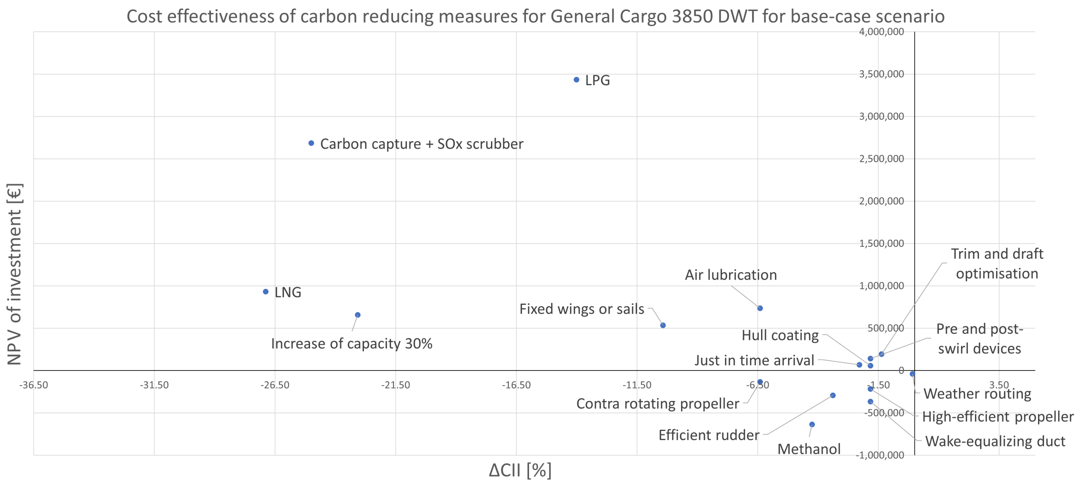


Figure P.1.: Cost effectiveness for carbon reducing measures of General Cargo 3850 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔCII of -91% and a NPV of €-54,978,000. Hydrogen has a ΔCII of -91% and a NPV of €-92,651,000. Ethanol has a ΔCII of +22% and a NPV of €-16,698,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

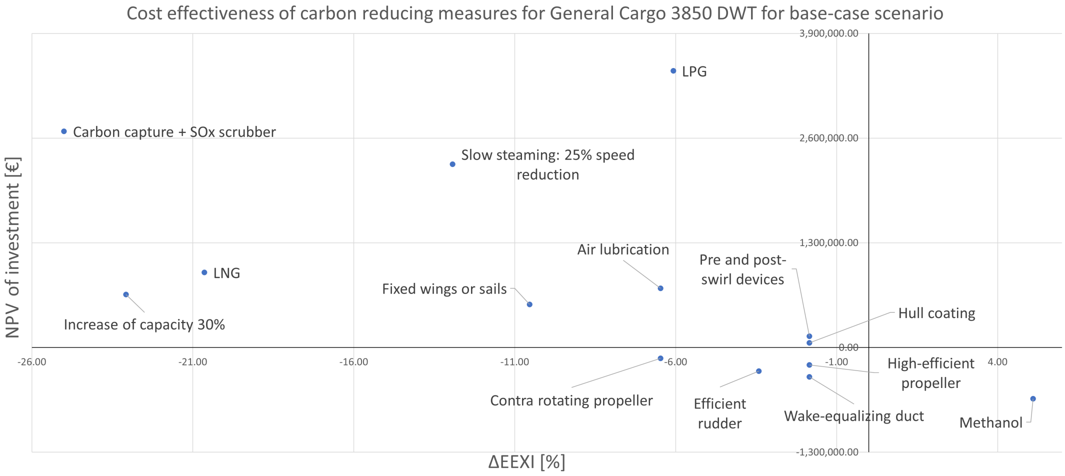


Figure P.2.: Cost effectiveness for carbon reducing measures of General Cargo 3850 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔEEXI of -92.45% and a NPV of €-54,978,000. Hydrogen has a ΔEEXI of -92.45% and a NPV of €-92,651,000. Ethanol has a ΔEEXI of +40.20% and a NPV of €-16,698,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value. Interestingly, methanol has an increase in EEXI rating whereas its a decrease in CII rating. This can be explained by the different methods of calculation, the CII has an input for the actual fuel consumption and the EEXI uses the theoretical fuel consumption. This suggest that in reality ships sail below their operating point at 75% MCR.

General cargo 8000 DWT

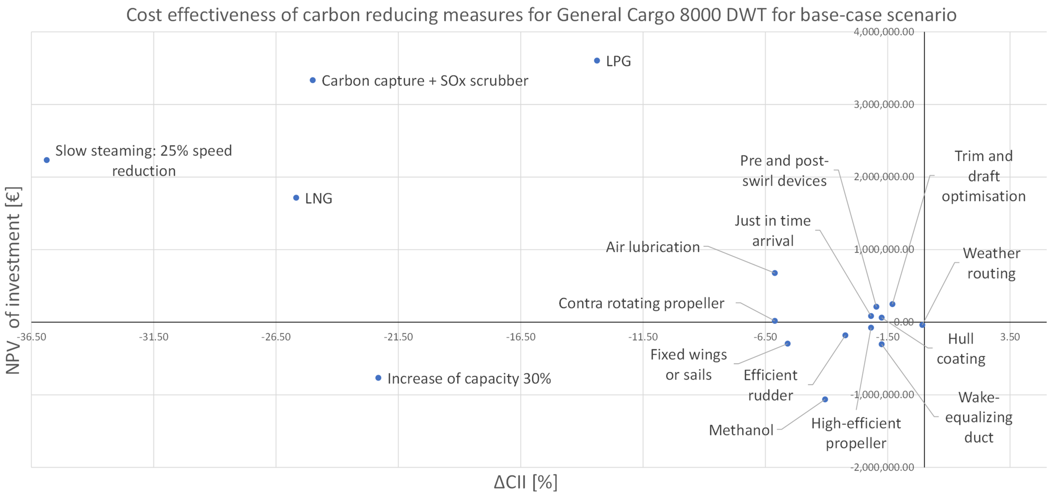


Figure P.3.: Cost effectiveness for carbon reducing measures of General Cargo 8000 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔCII of -87% and a NPV of €-72,389,000 . Hydrogen has a ΔCII of -87% and a NPV of €-115,638,000. Ethanol has a ΔCII of +22% and a NPV of €-17,657,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

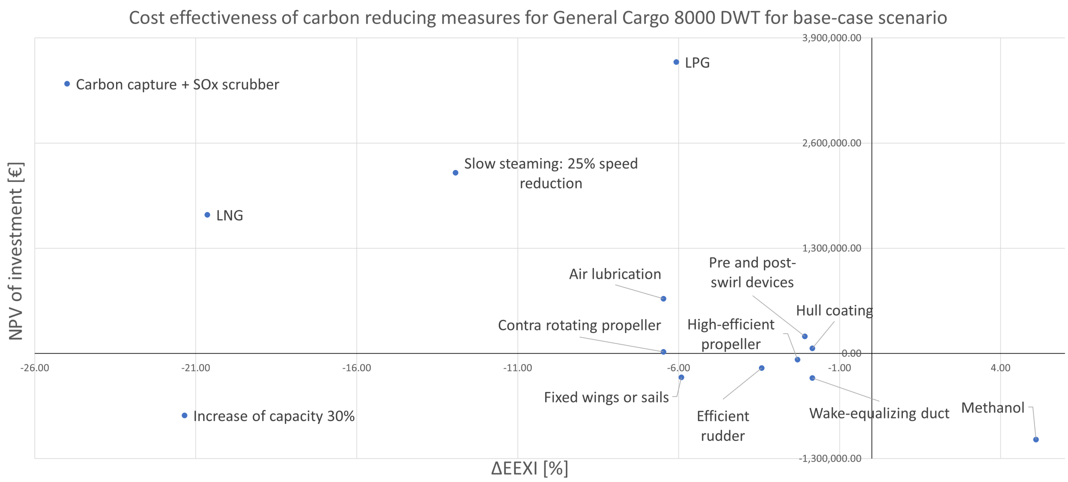


Figure P.4.: Cost effectiveness for carbon reducing measures of General Cargo 8000 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔEEXI of -92% and a NPV of €-72,389,000 . Hydrogen has a ΔEEXI of -92% and a NPV of €-115,638,000. Ethanol has a ΔEEXI of +40% and a NPV of €-17,657,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

General cargo 14500 DWT

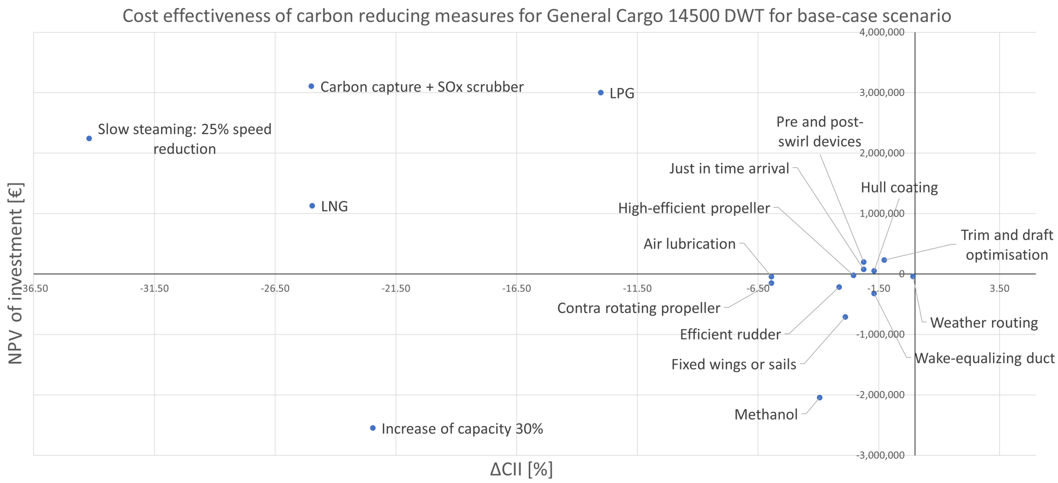


Figure P.5.: Cost effectiveness for carbon reducing measures of General Cargo 14500 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔCII of -85% and a NPV of €-118,646,000. Hydrogen has a ΔCII of -85% and a NPV of €-176,455,000. Ethanol has a ΔCII of +22% and a NPV of €-17,912,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

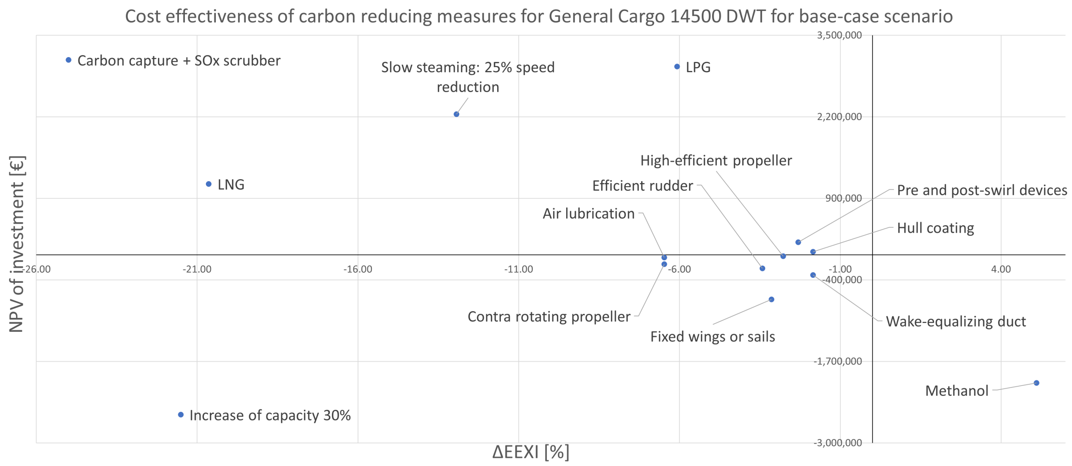


Figure P.6.: Cost effectiveness for carbon reducing measures of General Cargo 14500 DWT vessel for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔEEXI of -92% and a NPV of €-118,646,000. Hydrogen has a ΔEEXI of -92% and a NPV of €-176,455,000. Ethanol has a ΔEEXI of +40% and a NPV of €-17,912,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

Container vessel 750 TEU / 9300 DWT

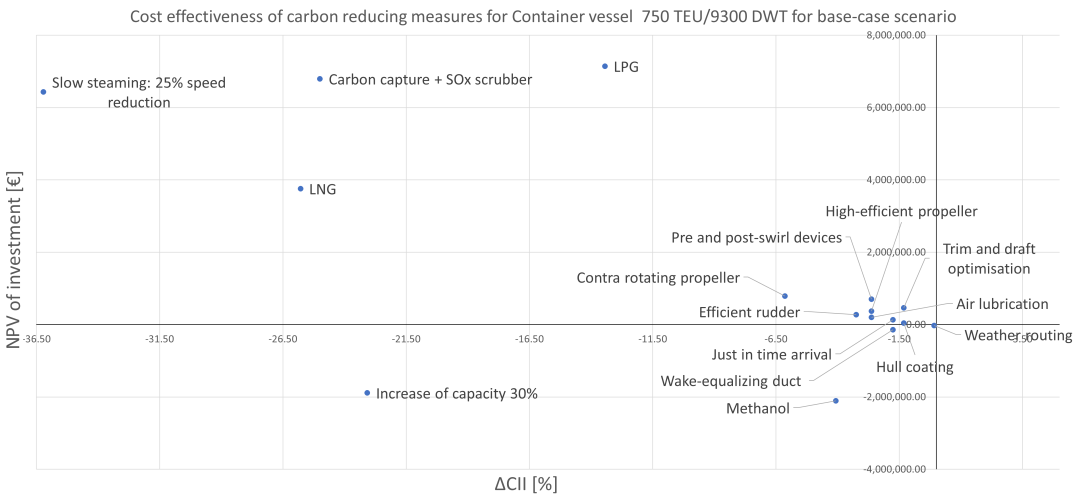


Figure P.7.: Cost effectiveness for carbon reducing measures of Container vessel 750 TEU/9300 DWT for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔCII of -88% and a NPV of €-85,545,000. Hydrogen has a ΔCII of -88% and a NPV of €-154,536,000. Ethanol has a ΔCII of +22% and a NPV of €-31,545,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

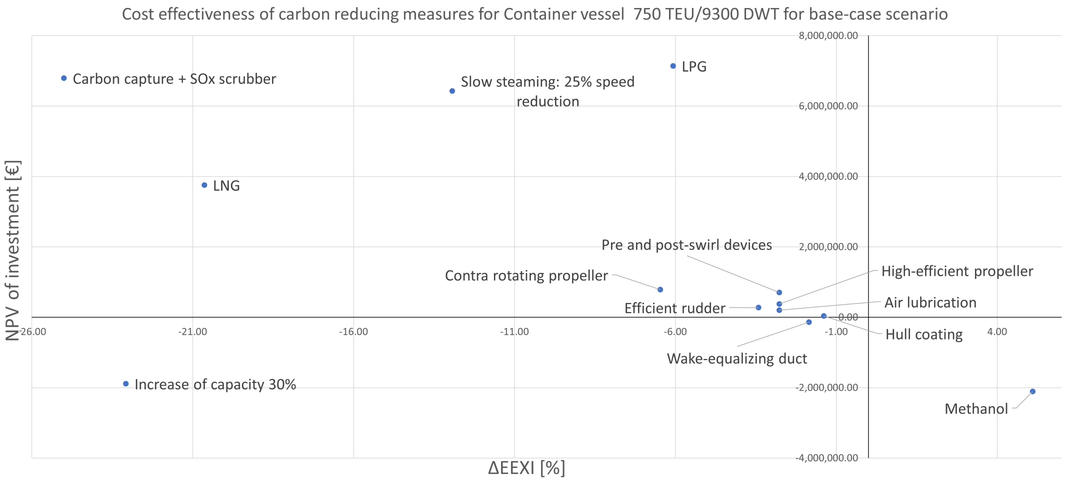


Figure P.8.: Cost effectiveness for carbon reducing measures of Container vessel 750 TEU/9300 DWT for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔEEXI of -92% and a NPV of €-85,545,000. Hydrogen has a ΔEEXI of -92% and a NPV of €-154,536,000. Ethanol has a ΔEEXI of +40% and a NPV of €-31,545,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

Product tanker 9300 DWT

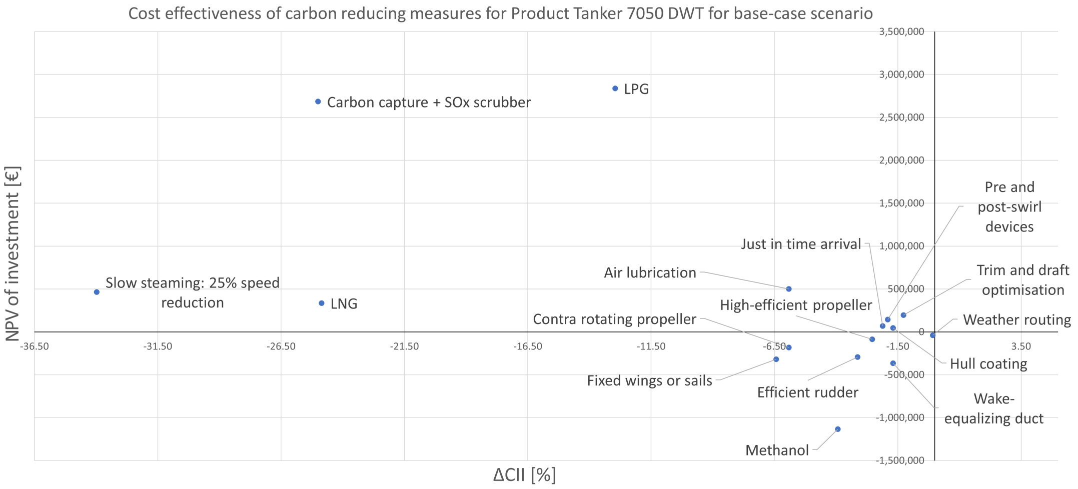


Figure P.9.: Cost effectiveness for carbon reducing measures of Product tanker 7050 DWT for base-case price scenario (excluding fully electric, hydrogen and ethanol)

The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔCII of -84% and a NPV of €-104,281,000. Hydrogen has a ΔCII of -84% and a NPV of €-154,680,000. Ethanol has a ΔCII of +21% and a NPV of €-17,919,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

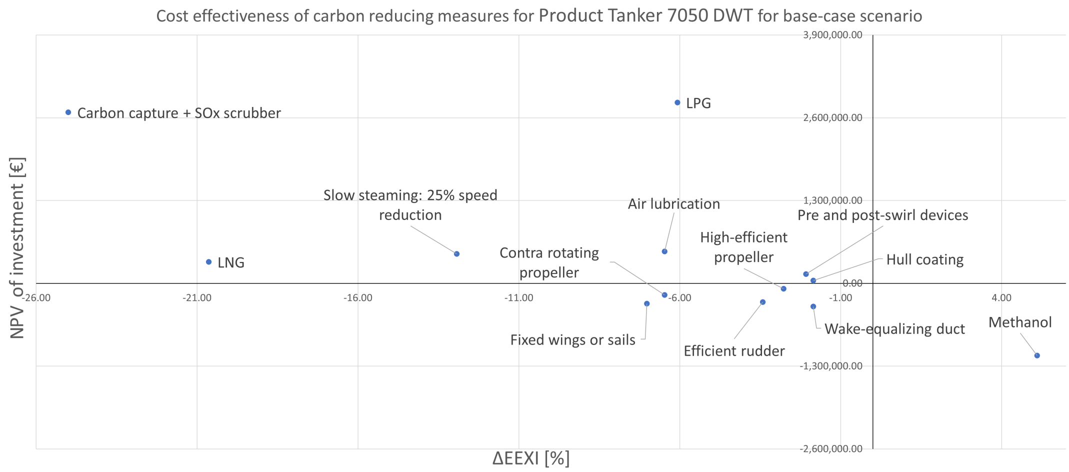
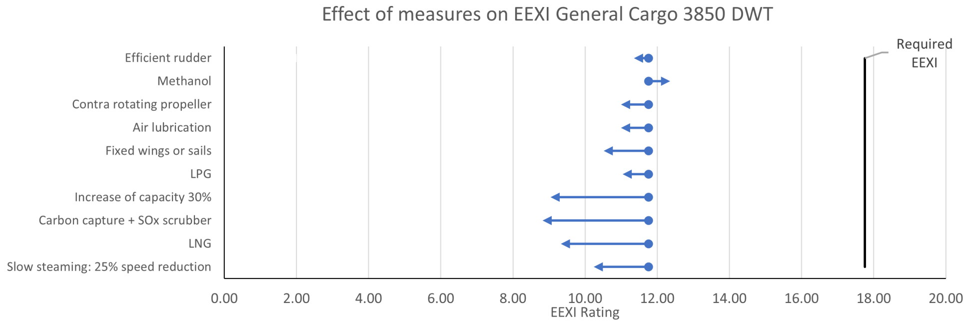
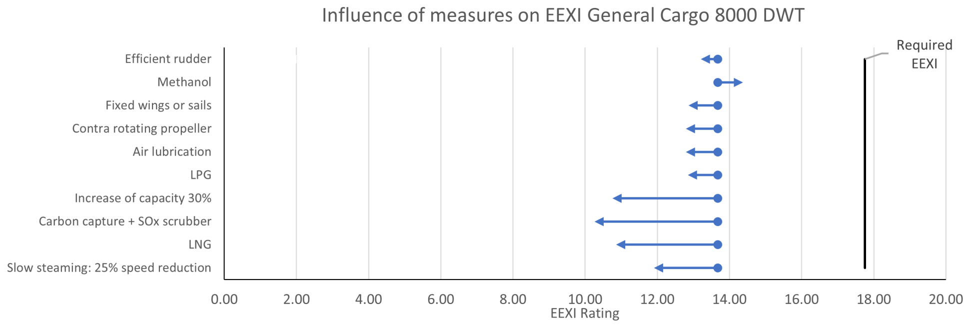


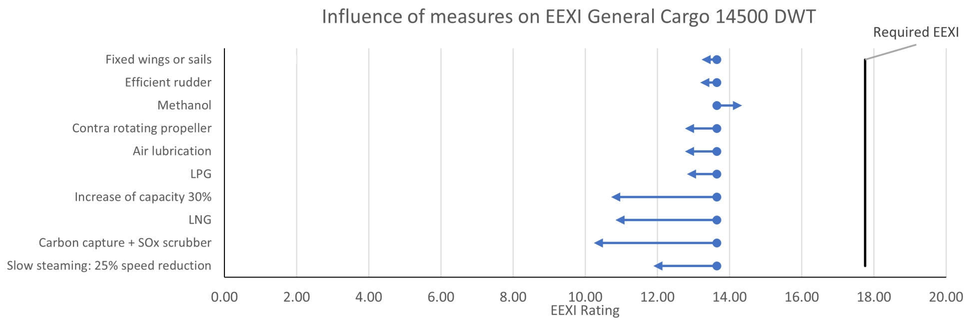
Figure P.10.: Cost effectiveness for carbon reducing measures of Product tanker 7050 DWT for base-case price scenario (excluding fully electric, hydrogen and ethanol)

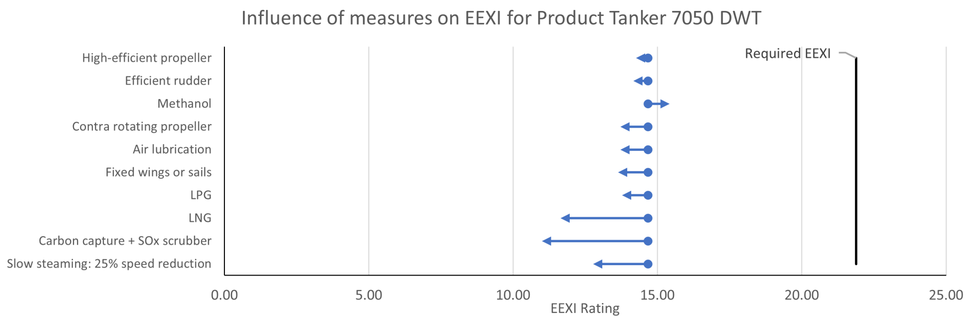
The values for the measures; fully electric, hydrogen and ethanol are not shown due to their extreme nature. Fully electric has a ΔEEXI of -92% and a NPV of €-104,281,000. Hydrogen has a ΔEEXI of -92% and a NPV of €-154,680,000. Ethanol has a ΔEEXI of +40% and a NPV of €-17,919,000. The positive ΔCII can be explained by the low η_e and the low energy content of the fuel relative to its Cf value.

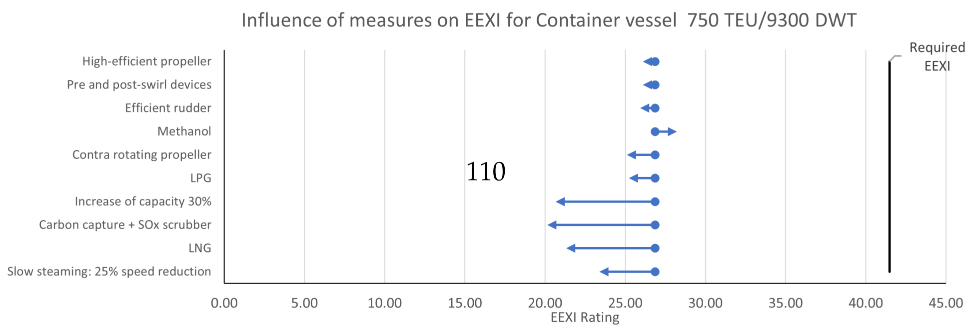
Q. Effect of measures on the EEXI for all reference vessels











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Colophon

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