UNIVERSITY OF PIRAEUS

DEPARTMENT OF MARITIME STUDIES

MSc Sustainability and Quality in Marine Industry

INCLUSION OF SHIPPING IN THE EU ETS: ASSESSMENT OF THE IMPACTS AT THE SHIP LEVEL

Dimitris Andreas Plataniotis

Submitted to the Department of Maritime Studies of the University of
Piraeus as part of the requirements for the award of the Postgraduate
Diploma in “Sustainability and Quality in the Marine Industry”

Piraeus

December 2024

Authenticity Declaration: "The person who conducted this dissertation thesis bears the entire responsibility to determine the fair use of the material, which is defined on the basis of the following factors: the purpose and nature of the use (commercial, non-commercial or educational), of the nature of the material, which it uses (texts, tables, figures), of the percentage and of importance of the section, which it uses in relation to the whole text under copyright, and the possible consequences of its use in the market or in more general value of the copyrighted text".

This diplomatic thesis was unanimously approved by the Three-Member Board Committee appointed by the Management of the School of Maritime Studies in accordance with the Operating Regulation of the masters' program.

The members of the Committee were:

- Assist. Professor Stefanos Chatzinikolaou (Supervisor)
- Professor Fani Sakellariadou
- Professor Maria Poulia Boile

The approval of the thesis by the School of Maritime Studies of the University of Piraeus does not imply acceptance of the author's opinions.

Contents

Figures

Tables

Abstract

The inclusion of shipping in the European Union Emissions Trading System (EU ETS) introduces significant operational and financial challenges, as ship operators face direct costs linked to carbon emissions. This study establishes a comprehensive methodology for assessing the EU ETS impact at the ship level, focusing on vessel-specific data collection and validation, operational parameter analysis, emissions quantification, and calculation of EU allowance requirements. Using real data from ship operation, covering a period from 2021 to mid-2024, the research ensures the credibility and accuracy necessary for informed decision-making. The findings emphasize that ship operators must adopt robust systems to continuously monitor and verify their EU ETS exposure, enabling compliance and cost-effective operational adjustments. By bridging regulatory requirements and practical implementation, this study provides a valuable framework for navigating the complexities of maritime decarbonization under the EU ETS framework.

Keywords: EU ETS, operational efficiency, CO2 emissions, EU allowances

1. Introduction

2024 marks the first year of the inclusion of shipping in the EU Emissions Trading System (ETS), which represents a significant step towards addressing maritime greenhouse gas (GHG) emissions. The dissertation assesses the energy efficiency and carbon intensity at the ship level, with the objective to determine compliance with the ETS regulation while at the same time achieving other energy efficiency targets set by IMO, i.e. the Energy Efficiency Index for Existing Ships (EEXI), and the Carbon Intensity Indicator (CII). The study will utilize real data from ship operation to calculate the allowances relevant to ETS, as well as overall ship energy efficiency.

1.1. Maritime emissions

Maritime shipping is a vital component of global trade, responsible for transporting approximately 90% of the world's goods (ICS, 2015). This staggering figure highlights the sector's importance in facilitating international commerce and enabling the global supply chain. The vast majority of raw materials, agricultural products, manufactured goods, and energy resources are moved across oceans and seas, reflecting the efficiency and capacity of maritime transport. According to United Nations (UNCTAD, 2023), around 12 billion tons of goods are transported annually by sea, underscoring the industry's role in supporting economic activities and development worldwide. In addition, maritime industry's ability to handle large volumes at relatively low costs (economy of scale), makes it indispensable for global trade, providing essential connectivity between markets and fostering international economic integration.

According to the information by International Energy Agency, global energy-related CO2 emissions grew by 0.9% in 2022 and 1.1% in 2023, reaching a new record high of 37.4 gigatons CO2 (IEA, 2022). Reference to the chart 1 illustrating the share of emissions by sector, transport accounts for about 24% of global CO2 emissions. Within the transport sector, maritime shipping is a key component responsible for about 10.9% of transport-related emissions. That means shipping contributes around 2.6% (4th IMO Study) of the total global CO2 emissions, underscoring its substantial impact on global climate change, despite its critical role in international trade.

The chart from the International Council of Clean Transportation (ICCT) further supports this breakdown (Figure 2). It shows that out of 8.8 gigatons of CO2 emissions from the transport sector, road transport accounts for the majority, followed by aviation and shipping. The latter's share is approximately 10.9%, aligning with IEA's data on sectoral emissions. This proportion highlights the importance of addressing emissions from maritime activities as part of broader efforts to mitigate climate change. By focusing on this 11% slice of transport emissions, policymakers and industry leaders can implement targeted strategies to reduce the environmental footprint of global shipping operations.

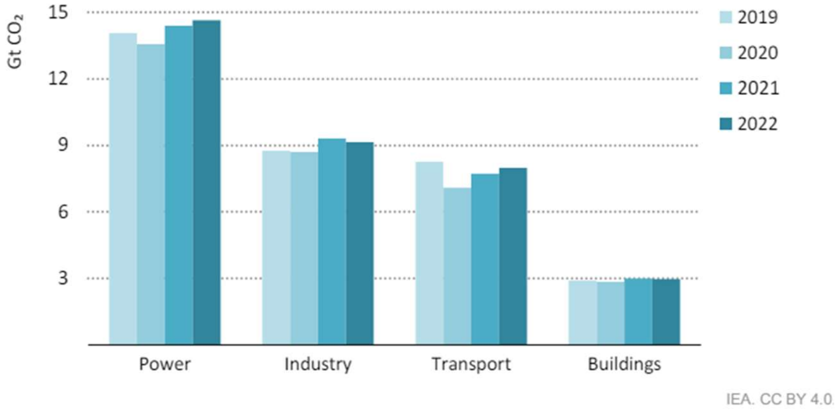
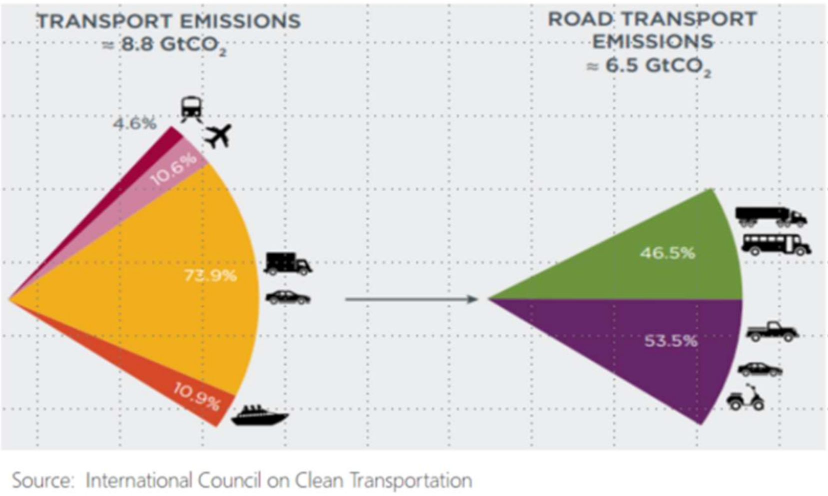


Figure 1: CO2 Emissions by sector (IEA, 2022)



Source: International Council on Clean Transportation

Figure 2: Breakdown of transport emissions (ICCT, 2017)

The decision to include shipping into the EU ETS aims to incentivize emission reductions within the sector, promoting cleaner technologies and more efficient operational practices. Incorporation of shipping into the EU ETS presents both challenges and opportunities at the ship level. Ship operators will need to navigate the vessel’s environmental performance, while the same time facing increased operational costs due to emissions allowances.

Therefore, assessing the impacts at the ship level is crucial for understanding how these regulatory changes will affect the operational and financial dynamics of the maritime industry, ultimately contributing to more sustainable shipping practices.

2. Theoretical background

In the face of escalating climate change challenges, the maritime industry, long perceived as a silent giant of global trade, now stands at the crossroads of a transformative era. The inclusion of shipping in the European Union Emissions Trading System (EU ETS) marks a pivotal step towards a greener and more sustainable future. As the EU amplifies its efforts to curb greenhouse gas emissions, integrating the maritime sector into its flagship climate policy, not only underscores the urgency of reducing carbon footprints, but also highlights the complex interplay between international regulations and regional ambitions. This dissertation delves into the intricacies of this groundbreaking policy shift, exploring its potential to lower carbon intensity on maritime practices, align with the International Maritime Organization's energy efficiency targets, and set a precedent for vessel fleet environmental governance.

2.1. Overview of Climate Change and Maritime Emissions

According to the European Commission, including the maritime sector in the EU ETS is essential for reducing greenhouse gas emissions and helping the EU meet its targets, such as achieving climate neutrality by 2050 (European Commission, 2023). This dissertation will dive in the specific targets set by the EU, analyze the current emission levels of the maritime sector, and estimate the potential reductions through the EU ETS. We will explore how cap-and-trade system of the EU ETS can provide economic incentives for shipping companies to reduce their emissions. This involves assessing the effectiveness of market-based mechanisms in encouraging the adoption of cleaner technologies and operational practices, drawing on findings from the IMO 4th GHG Study, which provides comprehensive data on global shipping emissions and trends (IMO, 2020)

A regulatory framework analysis will take place to provide an in-depth examination of the policy established by the EU for integrating shipping into the EU ETS. It will cover key components such as monitoring, reporting and verification (MRV) requirements, emission allowances, and the timeline for implementation as outlined by the European Commission (European Commission, 2023). Subsequently, the dissertation will explore the challenges shipping companies face in complying with the new regulations, including financial, operational and logistical hurdles. Insights from DNV's reports on maritime compliance will be used to assess industry readiness and highlight best practices for achieving compliance (DNV, 2023)

Including shipping in the EU ETS is expected to have significant economic impacts (European Commission, 2023). The dissertation will analyze potential costs for shipping companies, including the purchase of emission allowances and possible changes in vessels’ operational patterns.

2.2. Regulatory Framework

2.2.1. IMO Regulations

The International Maritime Organization (IMO) has taken significant steps to reduce greenhouse gas (GHG) emissions from international shipping, beginning with the 2011 amendments to MARPOL Annex VI. This included the introduction of the Energy Efficiency Design Index (EEDI) (MEPC 62, 2011), which mandates that new ships meet specific energy efficiency standards. Additionally, the Ship Energy Efficiency Management Plan (SEEMP) was made compulsory for all ships, encouraging the adoption of energy management practices.

In 2018, the IMO adopted its Initial GHG Strategy (MEPC 72, 2018), setting a target to reduce GHG emissions from international shipping by at least 50% by 2050 compared to 2008 levels, with the ultimate goal of phasing them out entirely within this century. This strategy outlined short-term measures, such as enhancing the EEDI and SEEMP, and the introduction of new measures for existing ships. The strategy also emphasized the need for developing mid- and long-term measures, including new technologies and alternative fuels, and considering market-based measures (MBMs).

The IMO's Fourth GHG Study, approved and published in 2020 (MEPC 75, 2020), provided comprehensive data on shipping emissions and trends, offering a crucial foundation for developing further regulations and measures to achieve the targets set in the initial GHG strategy. This study is integral to understanding the progress made and the areas requiring further action.

In 2023, the IMO adopted the Carbon Intensity Indicator (CII) and Enhanced SEEMP (MEPC 76, 2021), further tightening the regulatory framework. The CII mandates ships to measure and report their carbon intensity annually, with the goal of reducing this over time. Additionally, the Enhanced SEEMP requires ships to develop an approved plan to meet annual CII targets, reinforcing the IMO's commitment to continuous improvement in energy efficiency and emission reductions.

In July 2023, the IMO adopted a revised GHG strategy (MEPC 80, 2023), significantly raising its decarbonization targets for international shipping. This strategy sets a goal of net zero greenhouse gas emissions by 2050, with more ambitious interim targets for 2030 and 2040 compared to the Initial Strategy. It also emphasizes the need to account for life cycle GHG emissions, from well-to-wake, to ensure that the full impact of fuel production and use is captured, avoiding emission shifts to other sectors. The strategy includes a target for at least 5% of the total energy used in international shipping to come from zero or near-zero GHG fuels by 2030, with an aspirational goal of 10%.

The agreement also introduces mid-term measures comprising a technical element, such as a goal-based marine fuel standard, and an economic element, like carbon pricing mechanisms (e.g., a levy). Substantial progress on these measures has been made in discussions at the Intersessional Working Group on Reduction of Greenhouse Gas (GHG) Emissions from Ships (ISWG-GHG 17) and (MEPC 82, 2024), with final decisions on mid-term policies expected at MEPC 83 in April 2025.

2.2.2. EU Climate Policy

The European Union (EU) has developed a robust framework to reduce GHG emissions from maritime transport, beginning with the Monitoring, Reporting, and Verification (MRV) Regulation in 2015 (EU, 2015). This regulation requires ships above 5,000 gross tonnages calling at EU ports to monitor, report, and verify their CO2 emissions, fuel consumption, and other relevant data from 2018 onwards. This initiative aims to increase transparency and data accuracy, laying the groundwork for more stringent future measures.

In 2023, the EU moved to include maritime emissions in its Emissions Trading System (ETS), as part of a broader effort to integrate maritime transport into the EU's climate policy (Fit for 55 package, EU ETS proposal, (EU, 2023)). This extension mandates that shipping companies purchase emission allowances for CO2 emissions from intra-EU and extra-EU voyages starting in 2024.

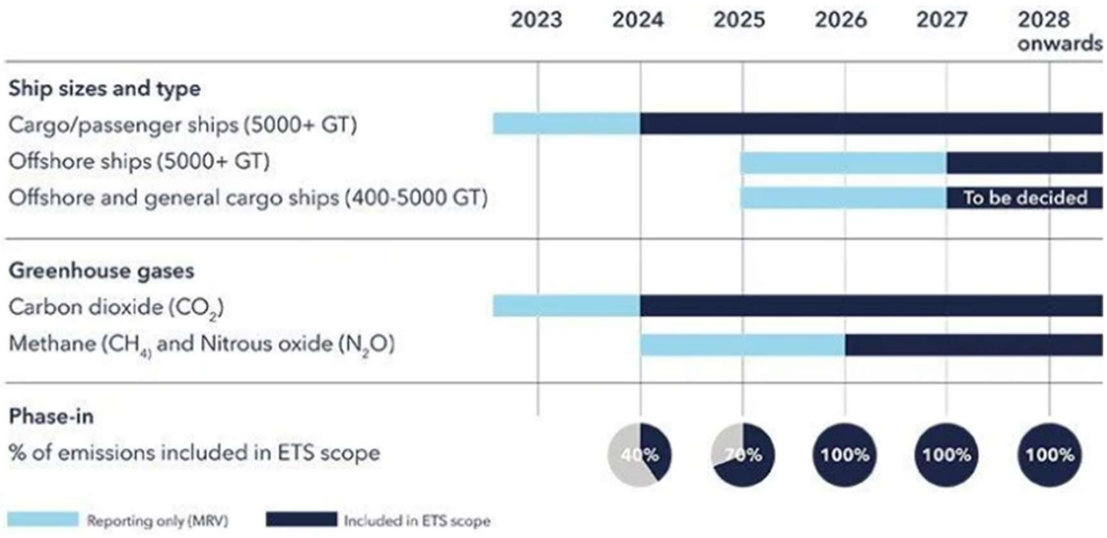


Figure 3: EU ETS Introduction timeline (Source: DNV 2024)

The European Green Deal, introduced in 2019, reinforces the EU's goal of becoming climate-neutral by 2050. Within this framework, the FuelEU Maritime Initiative mandates a GHG intensity limit, measured as CO2 emissions per MJ of energy used onboard ships, to drive the adoption of sustainable fuels and zero-emission technologies. It also requires ports to implement onshore power supply for vessels at berth by 2030, reducing dockside emissions. This initiative is central to the EU's strategy for decarbonizing maritime transport, aligning with its broader environmental objectives.

The Fit for 55 Package, proposed in 2021, includes a revision of the ETS Directive to integrate shipping emissions into the existing ETS framework. This package is part of the EU’s comprehensive plan to reduce GHG emissions by 55% by 2030 compared to 1990 levels. The EU's approach focuses on creating a stringent regulatory environment with clear targets and deadlines, ensuring that maritime transport contributes effectively to the EU's climate objectives.

2.2.2.1. Methods for monitoring CO2 emissions

Annex I of the regulation (EU, 2015) details the permissible methodologies for monitoring CO2 emissions from ships exceeding 5’000 GT engaged in voyages to, from, and between ports under the jurisdiction of European Union (EU) Member States.

The regulation specifies four distinct methods for monitoring CO2 emissions:

A. Bunker Fuel Delivery Notes (BDN) and periodic stock-takes of fuel tanks

This method relies on BDNs and periodic stock-takes of fuel tanks to determine the quantity of fuel consumed. The CO2 emissions are calculated by multiplying the amount of fuel consumed, as determined from BDNs, by a predefined emission factor specific to the type of fuel used.

B. Bunker fuel tank monitoring onboard

Under method B, continuous monitoring of the fuel tank is conducted to determine the volume of fuel consumed during a voyage. This method also involves the use of calibrated flow meters to ensure accurate measurements. CO2 emissions are then calculated based on the total fuel consumed and the corresponding emission factors.

C. Flow meters for applicable combustion processes

This approach employs flow meters installed in the fuel supply lines of the ship's main engine(s), auxiliary engines, and other combustion processes. By continuously measuring the flow of fuel consumed, CO2 emissions are directly calculated using emission factors.

D. Direct CO2 emissions measurement

Method D involves the direct measurement f CO2 emissions at the exhaust of the ship's engines using onboard CO2 sensors. This method provides real-time data on CO2 emissions and allows for precise calculation without reliance on fuel consumption data.

Each method outlined in Annex I has specific technical requirements and conditions under which it can be applied. The regulation permits ship operators to select the method best suited to their vessel's operations, provided it ensures accuracy, reliability and consistency in monitoring CO2 emissions. The chosen method must be clearly documented in the ship's monitoring plan and is subject to verification by an accredited verifier to ensure compliance with the regulation. These methods provide a structured framework for quantifying CO2 emissions, thereby contributing to the broader goals of environmental sustainability and regulatory compliance within the EU's maritime industry.

2.3. Literature Review

2.3.1. EU ETS as a market-based mechanism and its implications

The inclusion of maritime transport in the EU ETS represents a significant policy shift aimed at addressing the shipping industry's greenhouse gas (GHG) emissions.

According to Wang et al., this policy move is a critical step in the EU's broader climate strategy to achieve carbon neutrality by 2050. The authors highlight that the EU ETS, as a market-based mechanism, provides financial incentives for shipping companies to reduce their emissions through the purchase and trade of emission allowances. This system is expected to drive the adoption of energy efficient technologies and operational practices. However, the paper also points out the potential challenges and economic implications for shipping companies, including the financial burden of purchasing allowances and the need for significant investments in cleaner technologies and alternative fuels (Wang et al., 2021).

Furthermore, the study in question underscores the complexities and potential impacts of the EU ETS on global shipping practices. One of the critical concerns is the risk of carbon leakage, where emissions reductions within the EU could be offset by increases elsewhere if shipping routes are altered to avoid EU waters. The authors argue that for the EU ETS to be effective, it must be designed to minimize such risks and ensure global cooperation. In an attempt to mitigate this risk, EU has adopted a new policy including major international ports to its borders, within the scope of EU ETS (Transshipment Ports). The paper suggests that while the EU ETS presents opportunities for significant environmental benefits, it also requires careful implementation and coordination with international regulatory frameworks to avoid unintended economic and environmental consequences (Wang et al., 2021).

Floden et al. employed a mixed-method approach, using both quantitative and qualitative data to provide a comprehensive assessment of the EU ETS's implications for the shipping industry (Flodén et al., 2024). They highlight the necessity of a robust monitoring, reporting and verification (MRV) system to ensure accurate tracking of emissions and compliance. Moreover, the analysis underscores the importance of setting a sufficiently high carbon price to drive significant emission reductions, reflecting the policy's potential to transform the shipping industry's environmental footprint.

In addition to environmental impacts, the paper explores the impact of the EU ETS on modal split, considering how changes in shipping costs might influence the relative competitiveness of different transport modes such as rail, road, and inland waterways. The authors suggest the higher shipping costs could lead to a shift in freight transport towards less carbon-intensive modes, thereby contributing to overall emission reductions across the transport sector. However, they also caution about risk of carbon leakage, where shipping activities might relocate outside EU to avoid extra costs (Flodén et al., 2024).

Another critical analysis on various market-based measures (MBMs) designed to reduce GHG emissions from the shipping industry was performed by (Psaraftis et al. 2021). Key components of the analysis include the evaluation of the effectiveness, economic impact, and feasibility of different MBMs such as carbon pricing, emission trading systems, and fuel levies. The authors conclude that while each measure has advantages and challenges, a combination of these approaches, tailored to regional and global contexts, is essential for achieving significant emission reductions and supporting the transition to sustainable maritime transport.

2.3.2. IMO Regulatory Frameworks and standards

2.3.2.1. EEDI and EEXI

The Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) are pivotal regulatory frameworks aimed at enhancing the energy efficiency of new and existing ships respectively. The EEDI, established by the IMO (MEPC 62, 2011) mandates that new ships meet specific energy efficiency standards, calculated in grams of CO2 per tonne-mile. This phased approach, beginning in 2013, requires progressive improvements in energy efficiency for each phase, driving the adoption of advanced technologies and designs that reduce fuel consumption and CO2 emissions. The EEXI on the other hand, targets the existing fleet, ensuring limitation and retrofit technologies. The implementation of these regulations underscores the importance of mandatory enforcement mechanisms to achieve significant CO2 emission reductions across maritime industry (MMMCZCS, 2022, 2023b).

2.3.2.2. Ship Energy Efficiency Management Plan (SEEMP)

The ship energy efficiency management plan is a regulatory framework established by the IMO aimed at improving the energy efficiency of ships. It provides a systematic approach for monitoring and improving the operational efficiency of ships to reduce GHG emissions. SEEMP was introduced as part of the IMO’s efforts to address climate change and promote sustainable shipping practices. In July 2011, the Marine Environment Protection Committee (MEPC) adopted the SEEMP as part of amendments to MARPOL Annex VI (MEPC 62), which introduced the requirement for all ships of 400 GT and above to develop and implement SEEMP by January 1st, 2013. During MEPC 70 in 2016, IMO introduced the Data Collection System (DCS) for fuel oil consumption as an amendment to MARPOL Annex VI, coming into force in 2018. This was followed by MEPC 74 in 2019, where IMO adopted amendments to SEEMP to incorporate the EEXI and CII. These amendments aimed to further enhance the energy efficiency measure under SEEMP.

2.3.2.3. Carbon Intensity Indicator (CII)

The Carbon Intensity Indicator (CII) complements the EEDI and EEXI by focusing on the operational efficiency of ships. The CII measures the annual operational carbon intensity of vessels, calculated as grams of CO2 emitted per cargo-carrying capacity and nautical mile. This indicator drives improvement in operational practices, such as optimizing speed, route planning and maintenance schedules. However, optimizing CII ratings presents complexities that require transparent collaboration among stakeholders, including shipowners, operators, charterers, and port authorities (MMMCZCS, 2023b) . Effective communication and coordination are crucial to align operational strategies with CII targets (Nelissen et al., 2023).

3. Selection of energy efficiency measures

3.1. Technological Advancements

Flettner rotors or Rotor Sails are a promising energy efficiency technology gaining traction in the maritime industry. These vertical cylinders, installed on the deck of a ship, utilize the Magnus effect to generate lift and provide additional propulsion, thereby reducing the main engine's load and fuel consumption (Talluri et al., 2018). Current adoption rates are growing, given several major shipping companies incorporating Flettner rotors into their fleets (IMO, 2022).

Air lubrication systems (ALS) reduce the frictional resistance between the ship's hull and water by creating a layer of microbubbles along the full surface. The technology has shown substantial fuel savings and CO2 reduction potential (MMMCZCS, 2022). In addition, digital optimization tools such as advanced voyage planning, software and real-time performance monitoring systems, are crucial for enhancing operational efficiency, given can provide large fuel savings (MMMCZCS, 2023a). These tools use big data and machine learning algorithms to optimize routes, speeds and maintenance schedules, significantly reducing fuel consumption and emissions.

Dual fuel engines, which can operate on both conventional marine fuels and cleaner alternatives like liquified natural gas (LNG), are pivotal in the transition towards sustainable shipping (MMMCZCS, 2023a). These engines enhance energy efficiency by allowing ships to switch to most efficient and environmentally friendly fuel available.

Alternative propulsion technologies, such as battery-electric systems and hydrogen fuel cells, offer significant potential for reducing maritime CO2 emissions. These technologies are in various stages of development and demonstration, with battery-electric systems being more advanced and already used in short-sea shipping and ferries such as E-ferry Elen in Denmark (E-ferry, 2015) and Future of the Fjords vessel in Norway (The Fjords, 2018). Hydrogen fuel cells are still in early stages of adoption, however existing applications into operation in Belgium and Japan highlighting the success of such alternative propulsion systems (Energy Observer, 2017).

3.2. Operational Measures

Speed optimization is one of the most effective operational measures for reducing fuel consumption and CO2 emissions (MMMCZCS, 2023a). By reducing the cruising speed of a vessel, fuel consumption can be significantly decreased due to the cubic relationship between speed and fuel usage. For instance, reducing a ship's speed by 10% can result in fuel savings of approximately 15% and corresponding CO2 emissions reduction of around 18% (Corbett et al., 2009).

Optimizing voyage planning involves using advanced software and real-time data to select the most efficient routes, considering factors such as weather conditions, currents and port congestion. Effective voyage planning can lead to fuel savings of about 10% and emissions reductions of approximately 12%. By minimizing unnecessary detours and idle times, ships can achieve better fuel efficiency, reducing overall operational costs and emissions (MMMCZCS, 2022).

Regular hull cleaning is essential for maintaining a ship's hydrodynamic efficiency. Biofouling – the accumulation of marine organisms on the hull – increases drag, which can lead to higher fuel consumption. Periodic hull cleaning can result in fuel savings of up to around 9% and thereby significant emissions reductions (Adland et al., 2018).

3.3. Challenges and Opportunities with Alternative Fuels

Scaling up the production of alternative fuels like biofuels, methane, methanol and ammonia poses significant challenges, primarily due to substantial investment required for developing large-scale production infrastructure. Establishing facilities for alternative fuel production involves high capital expenditures and the need for technological advancements to ensure efficient and safe production processes (Reddy et al., 2023). Moreover, ensuring the availability of feedstock biofuels, access to biogenic CO2 for e-methanol and the development of safe handling and storage technologies for ammonia, are critical issues that need to be addressed (Deka et al., 2022). Given the limitations and constraints of individual fuel types, the maritime industry is likely to rely on a mix of alternative fuels to achieve decarbonization targets (MMMCZCS, 2022).

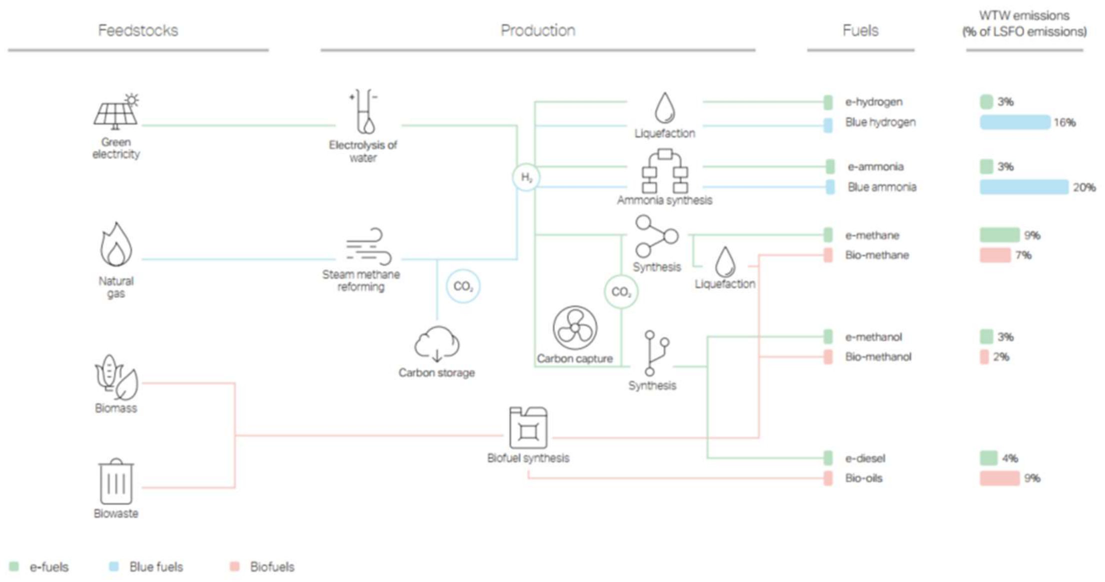


Figure 4: Alternative fuel production pathways in shipping (MMMCZCS, 2022)

E-fuels or electrofuels derive from green electricity, typically generated from renewable sources like wind or solar power. The green electricity is used to electrolyze water, producing hydrogen (e-hydrogen) with minimal emissions, shown to be just 3% of LSFO emissions. Hydrogen can further undergo ammonia synthesis to create e-ammonia, which similarly exhibits 3% of LSFO emissions. Additionally, combining hydrogen with captured CO2 through synthesis processes results in e-methanol (3% of LSFO emissions) and e-diesel (4% of LSFO emissions), providing versatile fuel options with significant emissions reductions (MMMCZCS, 2022).

Blue fuels are produced using natural gas as a feedstock through steam methane reforming, which generates hydrogen and CO2. The CO2 is captured and stored to minimize emissions. Blue hydrogen has a higher emission profile than e-hydrogen, at 16% of LSFO emissions. Blue ammonia, produced from blue hydrogen, exhibits 20% of LSFO emissions. These fuels represent a transition solution, leveraging existing natural gas resources while incorporating carbon capture technologies to mitigate environmental impacts (MMMCZCS, 2022).

Biofuels utilize biomass and biowaste as feedstocks, undergoing biofuel synthesis to produce bio-methane, bio-methanol, bio-oils and e-diesel. Bio-methane and bio-methanol boast low emissions of 7% and 2% of LSFO emissions respectively, while bio-oils exhibit higher emissions at 9%. These biofuels capitalize on the renewable nature of biomass and waste, offering a sustainable energy source with varying degrees of emission reductions depending on the specific fuel type feedstock and production process (MMMCZCS, 2022).

Such diversified approach ensures that the maritime industry can adapt to the varying availability and technological readiness of different fuel types, thereby enhancing the resilience of the fuel supply and realize a net-zero shipping future (Ramsay et al., 2023).

3.4. Penetration of alternative fuels in newbuilding orderbook

Reference below figure 4 by DNV Alternative Fuels Insight, alternative fuels make up a very small portion of the existing fleet (0.74%), indicating that the current fleet is overwhelmingly powered by conventional fuels. The percentage of ships on order using alternative fuels is significantly higher (15.96%), showing a growing trend towards adopting alternative fuels in newbuilds. The highest adoption rate is seen in new contracts, where 21% of new ships are being designed to use alternative fuels. The pie charts clearly depict that methanol is the fastest growing alternative fuel in new contracts over the last 12 month, making up to 10% of these contracts. LNG follows closely behind with 7% in new ships contracts and 8.74% in ships on order.

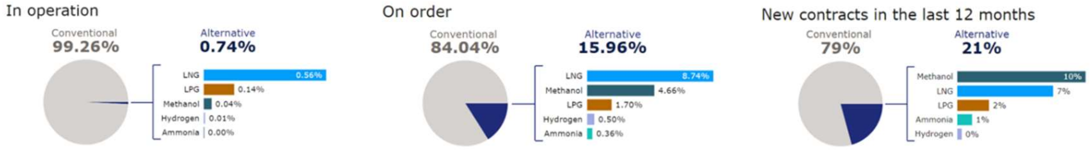
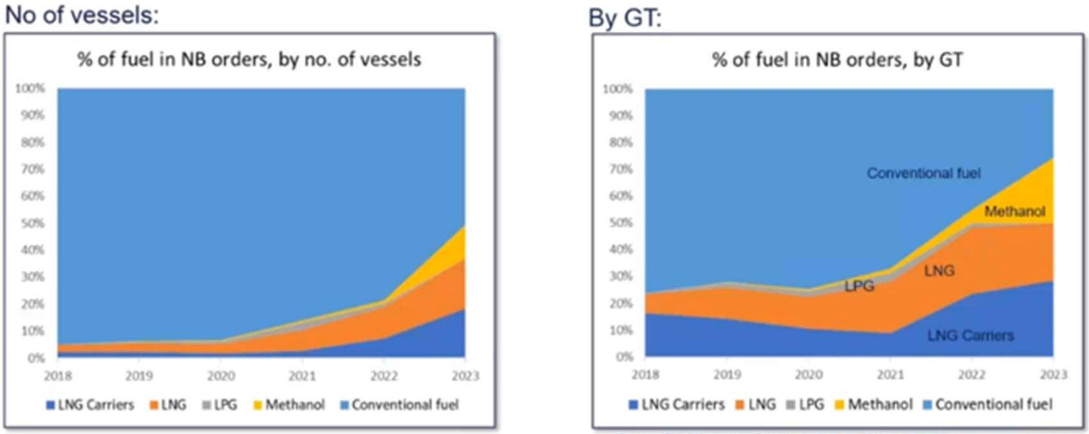


Figure 5: Percentage of fleet using conventional vs. alternative fuels

(Source: DNV AFI 2024)

The graph in figure 5 illustrates the slow but increasing adoption of alternative fuels in newbuilding orders for international shipping from 2018 to 2023. The left chart shows the percentage of newbuilding (NB) orders by number of ships, while the right graph shows the percentage of NB orders by gross tonnage (GT).



Source: DNV Alternative Fuels Insight - https://afi.dnv.com/.

Figure 6: Newbuilding orders with alternative fuels (Source: DNV AFI 2024)

Quantifying the adoption rates by number of vessels, in 2018 to 2019, there is almost a negligible adoption of alternative fuels, with conventional fuels dominating nearly 100% of orders. This was followed by a slight increase over the next two years, which appears primarily in LNG and LPG but not more than 10%. Starting in 2022 we see a noticeable increase, particularly in LNG, with methanol starting to appear. By 2023, alternative fuels make up approximately 20%-30% of newbuilding orders.

The right line graph illustrates similarities to the number for vessel, with almost negligible adoption of alternative fuels in 2018 to 2019. Between 2020 and 2021 there is a significant increase in LNG fueled ships by gross tonnage of about 45%. It can be clearly seen that there is a sharp increase in LNG, LPG and methanol in 2022 to 2023, where alternative fuels account for nearly 50% of the gross tonnage in newbuilding orders.

While the adoption of alternative fuels in international shipping is progressing slowly, there is a clear upward trend, especially in the last couple of years. It is evident that LNG has the fastest uptake among alternative fuels during this period. By 2023, LNG carrier and LNG-fueled ships constitute a substantial portion of the newbuilding orders by both the number of vessels and gross tonnage. Methanol and LPG fueled ships are also gaining traction, albeit at a slower rate compared to LNG fueled ships.

4. Methodology

The inclusion of shipping in the EU ETS introduces a direct cost associated with carbon emissions, which can substantially influence the operational expenses of ship operators. A detailed understanding of these financial implications is essential for enabling operators to comply with the regulatory framework effectively while also identifying strategies to mitigate associated economic risks.

The work implements a systematic methodology to calculate operational and financial metrics by leveraging ship's data collected from available noon reports. The process starts with the iterative validation of noon report data to ensure accuracy and reliability for the analysis. Following the validation step, key operational parameters such as vessel speed, idle times and Carbon Intensity Indicator (CII) are calculated. Subsequently, emissions are quantified based on fuel consumption data, forming the basis for determining the EU allowances. The following flowchart illustrates the comprehensive methodology adopted in this study, detailing each step from data collection to the calculation of EU ETS.

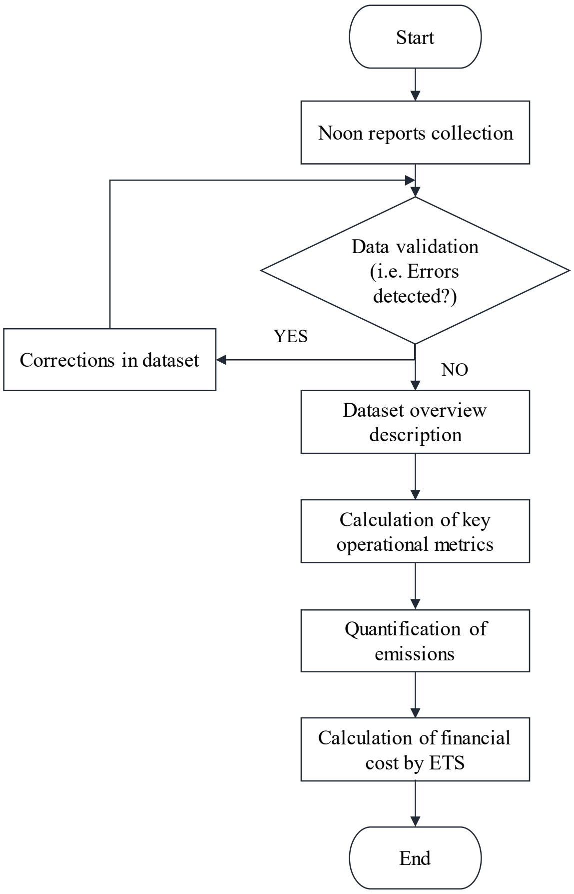


Figure 7: Methodology flowchart

4.1. Data collection

The collection of shipboard data required for compliance with the IMO Data Collection System (DCS) and the European Union Monitoring, Reporting, and Verification (EU MRV) regulation is conducted through a systematic approach. Typically, this procedure is executed by the ship's engineering team, with oversight by the Chief Engineer, and involves daily reporting through a structured document known as the Noon Report. The following table categorizes the key parameters recorded in the daily noon reports into three groups: vessel-specific data, weather conditions and engines’ performance metrics, providing a structured overview of the essential inputs for operational and technical monitoring:

Category	Parameters
Vessel specific data	- Observed distance (distance run)
	- Ship's position (latitude and longitude)
	- Draft (depth below waterline)
	- Miles to go
	- Estimated Time of Arrival (ETA)
	- Remaining on Board (fuel oil, lub. oil, freshwater,..)
Weather data	- Wind force and direction
	- Sea conditions (current, swell, and weather)
Engine performance data	- Exhaust gas temperature
	- Turbocharger RPM
	- Scavenging pressure and temperature
	- Seawater temperature
	- Engine room temperature
	- Number of generators in use
	- Generator power output

Table 1: Recorded parameters in noon reports

4.1.1. Calculation of fuel consumption

An integral part of the ship’s fuel oil monitoring equipment is consisted by the flowmeters and temperature sensors, which are installed in series with the fuel supply lines of each consumer, i.e. main engine, diesel generators and boilers. These readings are crucial for enabling the calculation of the CO_2 emissions associated with propulsion, power generation and steam production accordingly.

Figure 7 represents a simplified setup of the installed equipment onboard, enabling ship engineering team record and report the fuel consumption in the given period. The fuel flows from the fuel oil tank through the supply line, recording the mass of fuel at Flowmeter 1 (FM1) position. The consumer uses the fuel needed to produce work and left fuel is returning to the tank, recording its amount at Flowmeter 2 (FM2) position.

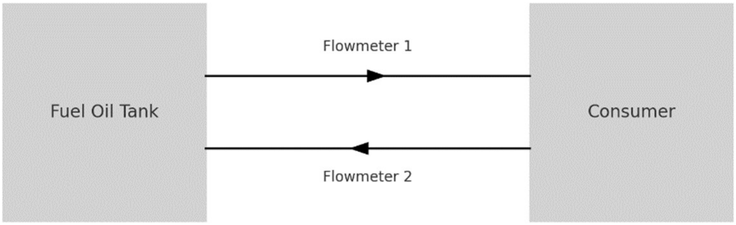


Figure 8: Schematic description of the equipment for ROB calculation

The flowmeter is a device that measures the flow rate of a fluid, and is used to measure the linear or non-linear, mass or volumetric flow of a gas or liquid. Flowmeters are known as flow gauges or flow measuring instruments. There are two broad types of flowmeters widely used in industries, volumetric and mass flowmeters. Volumetric flowmeters measure the fluid volume passing through a specific location, in a set period of time. They provide instantaneous analog, digital or pulse output of the volumetric flow rate of the liquid or gas. Mass flowmeters measure the mass flow rate that travels through a tube per unit of time. There are two basic types of mass flow meters, Coriolis and thermal mass flowmeters. The typical values indicated by such mass flow meter installed in the piping of the fuel consumers onboard ships are:

a) Flow Rate $[t/h]$: the instantaneous flow rate of the fuel being supplied to the consumer (e.g. main engine)
b) Density $[kg/l]$: the density of the fuel which is sued to convert volume-based flow measurements to mass-based measurements, which is required for accurate fuel consumption calculation
c) Temperature $[°C]$: the temperature of the fuel which affects the fuel's density and viscosity

d) Total mass $[t]$: the cumulative total amount of fuel has passed the flowmeter since last reset, which is particularly useful for monitoring long-term fuel consumption

The fuel oil consumption is then derived by comparing the readings of the cumulative consumption at two different times. To calculate the total fuel consumed during a given interval, subtract the initial from the final flowmeter reading using the formula:

$$Fuel\ Consumption\ [t] = (FM1_{END} - FM1_{START}) - (FM2_{END} - FM2_{START}) \quad (1)$$

4.2. Data validation and error correction

IMO DCS and EU MRV require ship operators to submit precise data on total fuel consumption, CO2 emissions, total distance traveled, time spent at sea, and transport work. Ships are required to operate under an approved monitoring plan that outlines the methodologies used for data collection. Data validation helps to identify discrepancies and ensures that the reported data aligns with the methodologies in the monitoring plan, thus meeting the legal requirements. Validated data is more likely to pass the scrutiny of verifiers, thus reducing the risk of non-compliance and enhances the credibility of ship operator.

The validation of operational data, particularly related to the carbon footprint of the vessel, is not only a regulatory necessity, but also a key component of the operator's environmental responsibility. This data is crucial for assessing the effectiveness of measures aimed at reducing greenhouse gas emission, such as optimizing engine performance, improving fuel efficiency, and implementing energy saving technologies. Validating this data ensures that it accurately reflects the vessel's operations, which is crucial for making informed decisions and optimizing performance.

In practical terms, the noon report data undergoes a rigorous validation process, i.e. a series of predefined formulas are applied on the data to identify and flag any inconsistencies or errors. In cases where discrepancies are detected, such as inconsistencies between consumed fuels and reported distance, corrective actions are taken. These corrections involve revisiting the original noon reports and making the necessary amendments to ensure accurate and logical continuity. Once all errors have been addressed, the data is prepared for further processing.

Key parameters which are thoroughly assessed during validation process are:

- Distance traveled in given period:

$$D_h \leq D_{rep} \leq V_{s_{max}} * 24 \quad (2)$$

where,

$V_{s_{max}}$: the maximum vessel speed based on MCR limit

D_h: great circle distance (Haversine formula)

- Time spent at sea

At this stage the formulas are comparing the time since previous report against the action of the noon report. The amount of time reported must reflect accurately the vessel's movement, i.e. sailing, drifting, shifting, etc.. This is crucial to obtain precise information about ship's operational profile, as well as percentage of time through the year where the ship remains idle, an important parameter for further analysis.

- Fuel consumption

This key parameter is directly connected to the CO2 emissions of the vessel and must be properly assessed for miscalculations, incorrect meter readings or data entry errors. The formula used is firstly comparing the total fuel oil consumption against the condition where the ship is operating under her most carbon-intensive operational profile. This is followed by the comparison of fuel oil consumed, remaining fuel oil, and any bunkers delivered onboard (BDN) using below scheme:

$$Fuel\ Consumption\ (FC) = FO\ ROB_{previous} - FO\ ROB_{current} + BDN \quad (3)$$

Misreporting of fuel oil remaining onboard ($FO\ ROB$) due to incorrect tank sounding measurements can be also assessed and in case inconsistencies are detected, one has to recheck tank soundings and consumption records, and perform the needed adjustments.

In summary, data validation in noon reports is crucial for detecting and correcting common errors, such as discrepancies in fuel consumption, power calculations and other key metrics. By applying specific formulas and cross-checking reported values, these errors can be efficiently identified and rectified, ensuring accurate and reliable reporting. This process not only supports regulatory compliance but also enhances operational efficiency.

4.3. Emission allowances (EUAs) calculation

The validated data is then imported into ShipForce software for detailed analysis. At this stage, the software is employed to identify whether and which voyages lie into the scope of EU ETS. After, the calculation of the CO2 emissions follows, for each voyage leg based on the reported fuel consumption, applying the appropriate emission factors as imposed by IMO (MEPC 76, 2021). The formula used to identify the mass (M) of CO2 emissions is as follows:

$$M = \sum FC_j \cdot C_{Fj} \quad (4)$$

where, FC_j is the total mass (in grams) of consumed fuel oil of type j, as reported under IMO DCS, while C_{Fj} represents the fuel oil mass to CO2 conversion factor. The following table presents the IMO-adopted values (IMO, 2020), which are used to convert the mass of traditional marine fuel oils into the corresponding CO2 emissions.

Fuel Type	**Carbon factor** $[\boldsymbol{ton\ CO_2/tonfuel}]$
HFO	3.114
LFO	3.151
MGO/MDO	3.206

Table 2: Emission factors of conventional fuels

The European Commission has introduced a phased approach for shipping companies to comply with the EU ETS, gradually increasing the proportions of emissions for which allowances must be surrendered over the years. This yearly fractions for purchasing allowances are as follows:

- 2024: 40% of the verified emissions
- 2025: 70% of the verified emissions
- 2026 and onwards: 100% of the verified emissions

These percentages apply to the emissions covered under the EU ETS which include:

- 100% of emissions from voyages between EU ports
- 100% of emissions from ships docked at an EU port
- 50% of emissions from voyages departing from an EU port to a non-EU port and vice versa

4.4. Operational Performance Analysis

Beyond compliance with the EU ETS, a comprehensive analysis of the ship's operational performance takes place, including the assessment of the Carbon Intensity Indicator (CII). The attained annual operational CII of individual ships is calculated as the ratio of the total mass of CO2 (M) emitted to the total transport work (W) undertaken in a given calendar year, as per below formulas:

$$attainedCII_{ship} = M/\,W \quad (5)$$

$$W = Capacity \cdot Distance \quad (6)$$

where, $Capacity$ represents the deadweight tonnage (DWT) of the vessel. For cruise passenger ships and vehicle carriers, we use gross tonnage (GT) instead. $Distance$, is the traveled nautical miles (nm) as reported under IMO DCS.

To facilitate the rating assignment, for each year from 2023 to 2030, there are four boundaries for the five-grade rating mechanism (MEPC 76, 2021). Hence a rating is assigned through comparing the attained annual operational CII of a ship with the boundary values. This analysis provides insights into how the ship's operation can be optimized to enhance both regulatory and overall efficiency.

5. Case Study: Application of Regulations

This chapter presents a detailed case study analyzing the operational data of a specific vessel from the UNIPI library to assess the impact of the EU ETS on its performance, emissions, and overall compliance. The dataset, covering the period from 2021 to mid-2024, forms the basis of this analysis. Using the methodology outlined in Chapter 4, the study evaluates key metrics, including fuel consumption, emissions, operational efficiency, and associated EU ETS allowance costs, to provide a comprehensive assessment of the vessel's compliance and financial implications under the EU ETS framework.

5.1. Vessel Particulars

Parameter	**Value**
Vessel type	Bulk Carrier
Main engine type	5S50ME-B Tier II
ME max. continuous rating [kW]	6.100
Deadweight tonnage [dwt]	38.650
EEDI [g-CO2/ton mile]	4.80
Year of built	2015
No. of auxiliary engine	3
AE max. continuous rating [kW]	745

Table 3: Vessel particulars

5.2. Key findings from data validation

In this section, we systematically identify common errors in the reported data, classify them, and outline their frequency over the years. The corrections are integral to ensuring that the data used for subsequent analysis is both accurate and reliable. Data entry errors in noon reports are categorized into three primary types: event type errors, ROB figure discrepancies, and distance inconsistencies. Event type errors occur when there is no logical continuity between consecutive reports (e.g., a "Drop Anchor" event not followed by "At Sea" or "Anchor Up"). ROB figure discrepancies arise when the reported remaining on board (ROB) fuel figures are inconsistent with the fuel oil consumed. Distance inconsistencies refer to discrepancies between the reported distance traveled and the actual distance derived from the vessel's positional data.

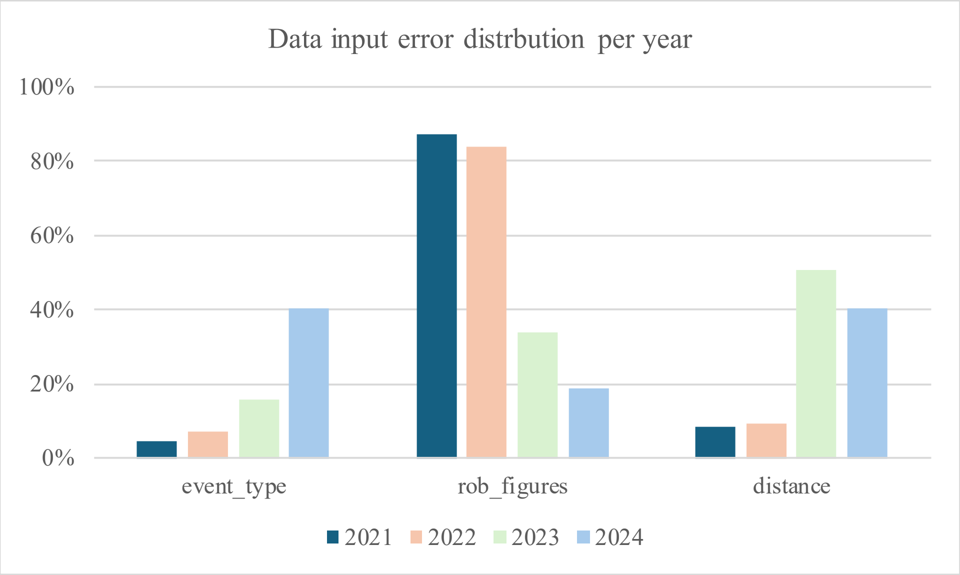


Figure 9: Type of errors upon validation

Figure 9 illustrates the frequency and distribution of different types of data entry errors for the vessel over the period 2021 to 2024. In 2021 and 2022, ROB figure errors dominated, accounting for over 80% of the errors. This suggests a significant issue with fuel consumption reporting, due to incorrect fuel type or quantity entries between noon reports. The minor presence of event type and distance errors indicates that operational events were relatively well-reported. By 2023, there is a notable reduction in ROB figure errors, with distance inconsistencies emerging as the most common error type of around 45%. This shift suggests that efforts to improve fuel data reporting were successful, but new challenges related to voyage distance calculations arose. Lastly in 2024, the distribution of errors becomes more balanced, with event type errors increasing to approximately 40%, distance inconsistencies remaining at a high level, and ROB figure errors decreasing to below 20%. This could indicate an improvement in fuel reporting accuracy but also a need to focus on improving the consistency of event reporting and voyage distance calculations.

5.3. Ship operational profile

Table 3 describes the sample dataset, presenting the total figures calculated for the period 2021 to 2024. The metrics included are the Carbon Intensity Indicator (CII), total distance traveled (nautical miles), CO_2 emissions (tons), the ratio attained/required CII as part of the compliance measures, and the annual energy efficiency rating. Additionally, the table provides the number of voyages and port stays per year.

Year	Distance [nm]	CO2 [MT]	CII [gCO2/dwt-nm]	# voyages	# port stays	att/req CII	Rating
2021	43420	11423	6.811	27	27	1.02	C
2022	51234	12317	6.223	41	41	0.94	B
2023	42477	10431	6.357	27	27	1.01	C
2024	24009	6090	6.566	22	22	1.06	D

Table 4: Total figures calculated from the sample dataset

The table illustrates that the vessel's operational profile is in line with the required CII regulatory limits, demonstrating competitiveness in terms of overall energy efficiency from a operational perspective. In 2022, the vessel's operational activity shows a notable increase in voyages, with an 18% rise in total distance covered compared to the previous year. This is accompanied by a 7.8% increase in CO_2 emissions. Despite the higher emissions, the vessel's energy efficiency improved, as reflected in the CII rating, which upgraded from "C" in 2021 to "B" in 2022, indicating enhanced performance. This suggests that the vessel effectively optimized its operations, maintaining regulatory compliance while increasing overall efficiency. In 2024, the dataset does not cover the full year, therefore, any conclusions drawn from 2024-data should account for this limitation in coverage.

5.3.1. Speed Frequency Analysis

The speed frequency analysis highlights the operational behavior of the vessel over time, showing patterns of speed optimization and energy efficiency improvements due to regulatory changes. The following charts, obtained from the ShipForce software (UNIPI academic license) and present the average sailing speeds for each year examined. The graphs indicate some unusually high peaks in speed values.

Figure 10: Visualization of ship speed upon validation 2021

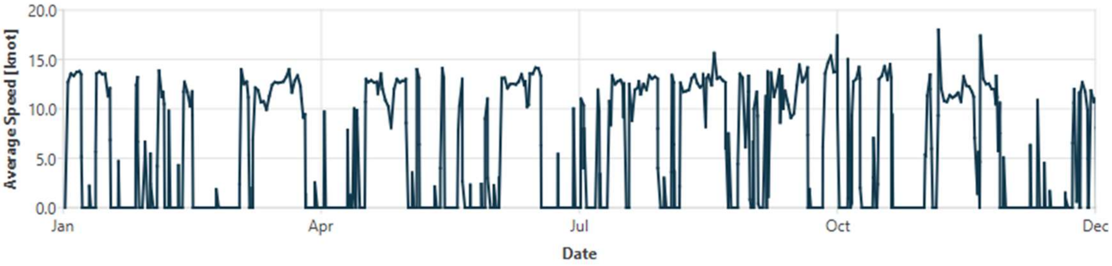


Figure 11: Visualization of ship speed upon validation 2022

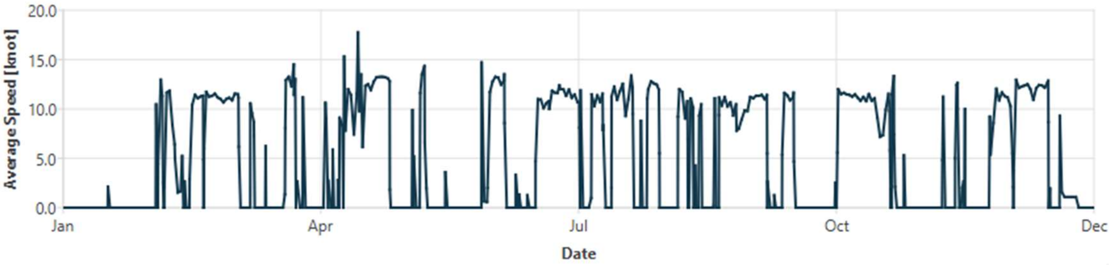


Figure 12: Visualization of ship speed upon validation 2023

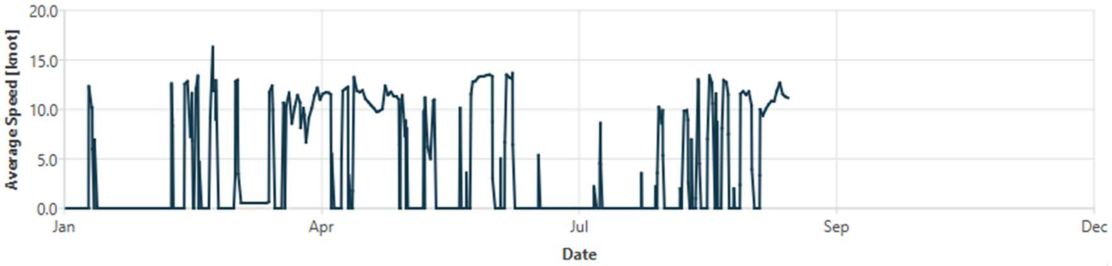


Figure 13: Visualization of ship speed upon validation 2024

The chart effectively displays any unexpected or erroneous values in the reported data, particularly in cases where speed peaks are beyond the range of ship operation. This visual detection aids in quickly identifying the errors or inconsistencies in the input data, corresponding to incorrect reported distance or time spent at sea. If these incorrect values remain in the dataset after validation, the historical database becomes unreliable, thus would undermine the credibility of any subsequent analysis or operational decisions based on the dataset.

As vessel speed increases, the distance covered per unit of time rises proportionally. This directly affects the ship's fuel consumption and CO_2 emissions, both of which are key components in calculating the operational efficiency index. In the following analysis, we will demonstrate how higher speeds significantly influence the overall operational index, highlighting the trade-off between faster transit times and increased fuel consumption, which impacts both efficiency and regulatory compliance under systems like the CII and EU ETS.

5.3.2. Speed and operational efficiency on voyage basis

This section examines the vessel's operational profile under varying loading conditions, focusing on speed and idle time as key parameters influencing the Carbon Intensity Indicator (CII). Using Python programming, voyages and port stays were identified, and CII was plotted against ship service speed and idle time per voyage leg. Speed affects fuel consumption and miles covered, while idle time reflects periods of inefficiency. These parameters were selected to offer a comprehensive understanding of the vessel's environmental performance and operational efficiency. It is important to note that this analysis focuses on the ship's operational profile rather than the specific implications of the EU ETS.

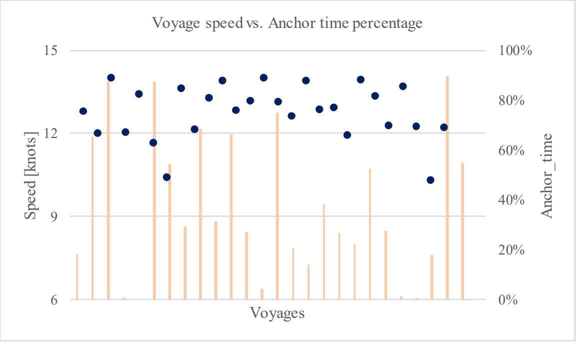


Figure 14: Speed vs anchor time per leg 2021

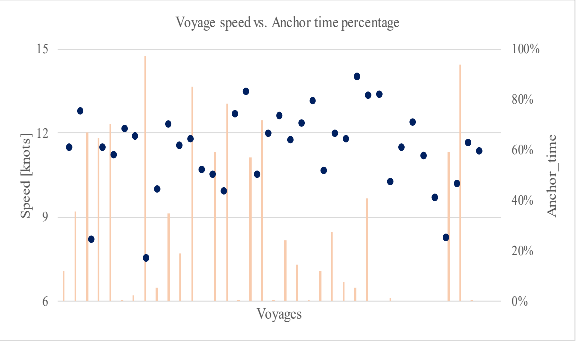


Figure 15:Speed vs anchor time per leg 2022

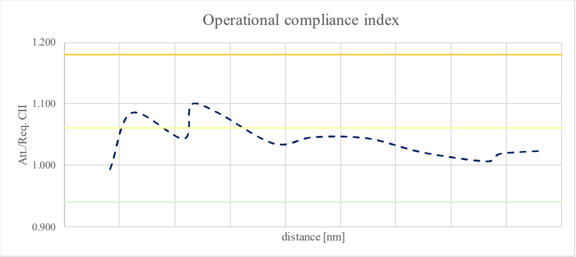


Figure 16: Total operational index performance 2021

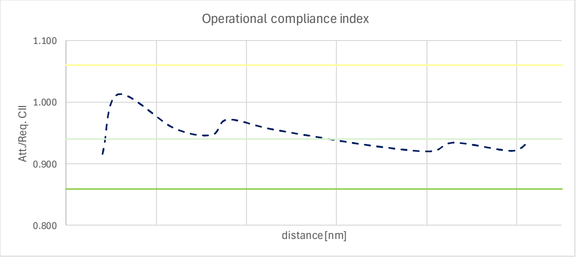


Figure 17: Total operational index performance 2022

The charts illustrate the average speed per voyage and the corresponding percentage of anchor time for each voyage leg during the years 2021 and 2022, as well as the performance of the ship in the operational compliance index (CII) over the total distance covered for this period.

Voyage speeds in 2021 remained relatively stable, ranging between 10 and 14 knots, with average speed 12.8 knots, while anchor time exhibited considerable variability. There was a notable range in anchor time across voyages, with some voyages experiencing anchor times as high as 80% of the total voyage duration, while others had minimal or no anchor time. The compliance index showed slight fluctuations around the required CII value (1.06) until the mid-point of the reporting period, during which anchor times displayed heightened variability. Following the mid-period, where anchor times decreased by 36% on average, there was a gradual improvement in the CII of about 7.7%.

The speeds remained within the 10 to 14 knots range in 2022, with 1.4 knots less on the average speed compared to the previous year, while anchor time percentages continued to vary widely. The 2022 operational index shows the vessel starting at B and hovering around this lower boundary (0.94). After the mid-point of the period, where there was a sharp reduction in anchor times by 67% on average, the vessel exhibited an improvement in its operational index by 15%, maintain its rating B throughout the year.

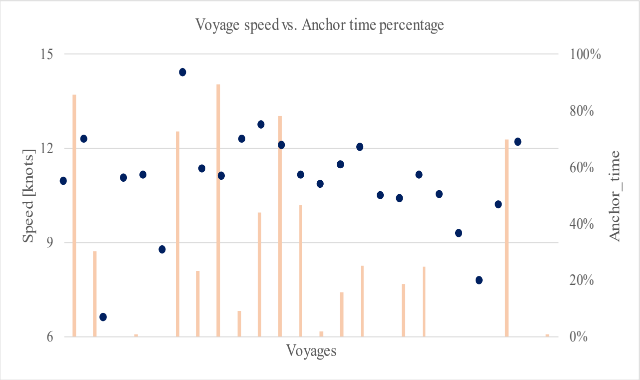


Figure 18: Speed vs anchor time per leg 2023

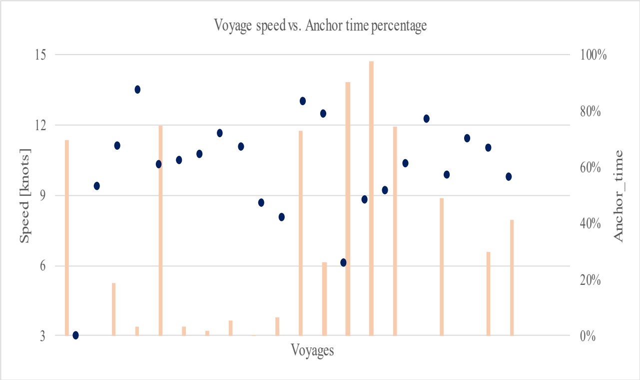


Figure 19: Speed vs anchor time per leg 2024

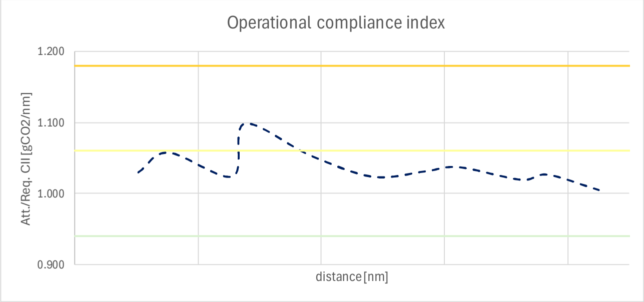


Figure 20: Total operational index performance 2023

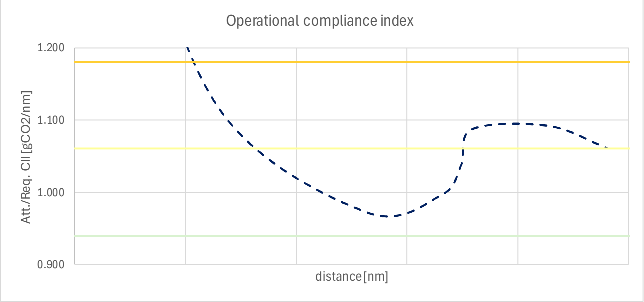


Figure 21: Total operational index performance 2024

In 2023, the average voyage speed varied between 9 and 14 knots, with an average speed reduction of 0.5 knots compared to the previous year. The first half of 2022, characterized by significant anchor times of about 40%, corresponded with fluctuations in the operational index, consistent with trends from previous years. Although the vessel concluded 2022 with a B rating, it returned to C (the required CII level), likely due to the initially augmented anchor times. As in prior years, the second half of the reporting period saw a notable reduction in anchor times of 67.5% on average, which was followed by a steady decrease in the CII value of 21% in total.

The speed distribution in 2024 appears more concentrated around 9 to 13 knots, though anchor time percentages still display variability. The CII ratio chart, starting above 1.20 with E rating, shows a striking improvement just above the lower boundary B at around 0.97 within the first half of the total reported nautical miles. However, following this period, the operational index increased above the required value, likely attributed to the almost doubled anchor times on average.

5.4. Fuel consumption onboard

The analysis of fuel consumption trends per consumer and fuel type onboard, is essential for ship operators to identify possible areas for energy usage optimization, as well as in assessing ships overall energy efficiency.

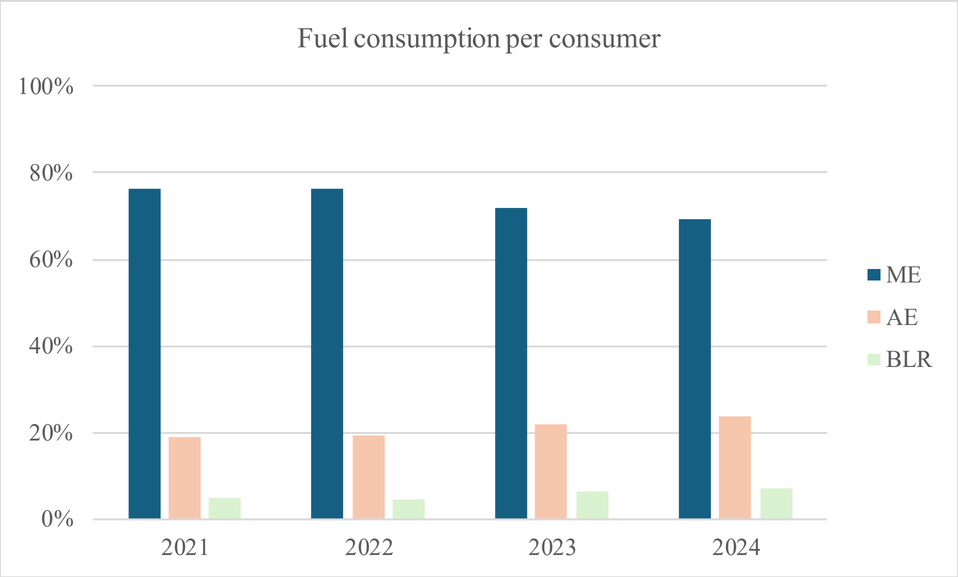


Figure 22: Percentage of fuel consumption onboard per consumer

The chart displays the fuel consumption per consumer onboard, divided into three categories: Main Engine (ME), Auxiliary Engines (AE), and Boilers (BLR) from 2021 to 2024. The Main Engine (ME) consistently dominates fuel usage, accounting for approximately 75-80% of the overall energy use per year. Auxiliary Engines (AE) show a steady fuel consumption percentage, ranging from 15-20%. Boilers (BLR), contributing the least, consistently account for around 5% of the total fuel consumption throughout the period.

5.5. Emissions Calculations

The annual CO2 emissions are calculated based on fuel consumption and emission factors. This highlights the impact of fuel efficiency as well as operational initiatives and regulatory enforcement on emissions reduction.

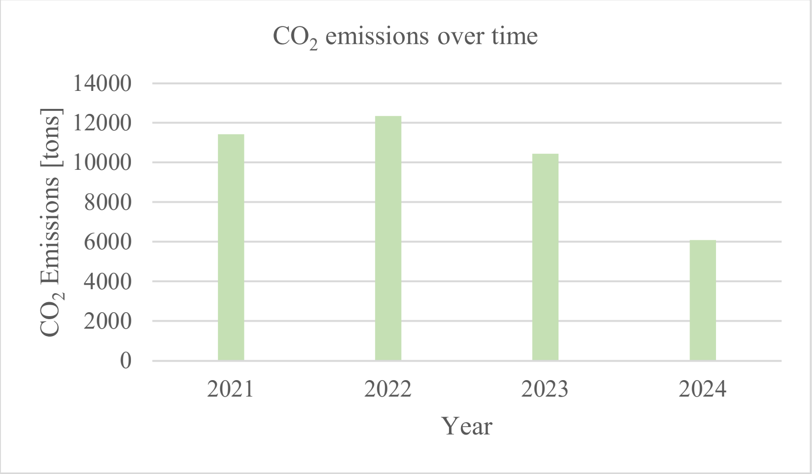


Figure 23: Total CO2 emissions per year

Figure 23 illustrates the total CO_2 emissions over time from 2021 to 2024. CO2 emissions accounted 11.400 tons in 2021 and increased slightly to 12.300 tons in 2022, corresponding to the additional miles covered. In 2023, there is a modest reduction to about 10.400 tons, and by 2024, emissions drop significantly to roughly 6.100, having almost covered 3 quarters of the reporting period.

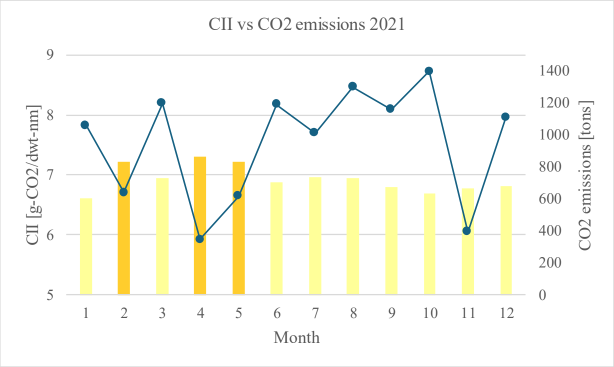


Figure 24: CO2 emissions and CII comparison 2021

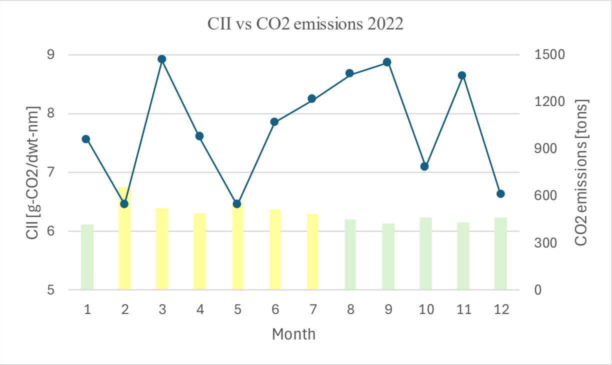


Figure 25: CO2 emissions and CII comparison 2022

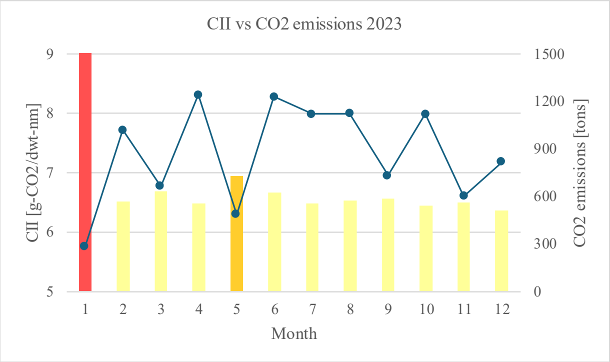


Figure 26: CO2 emissions and CII comparison 2023

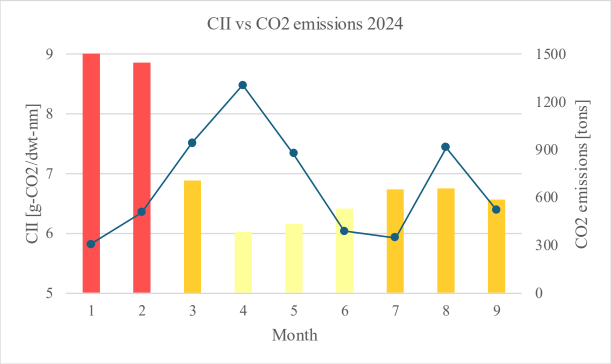


Figure 27: CO2 emissions and CII comparison 2024

The correlation between CO_2 emissions and the Carbon Intensity Indicator (CII), shows that increased emissions correspond to lower CII (Figures 23 to 26). These figures represent graphically the monthly operational data, highlighting the inverse connection between total emissions and CII performance. By plotting both metrics, the visualizations reinforce the trend that higher operational activity, contributing to elevated emissions, can improve the vessel's fuel efficiency when normalized over distance and cargo, leading to a more favorable CII rating.

5.6. Cost of emissions allowances

With the implementation of ETS, the cost per ton of CO2 needs to be considered, since results in a direct increase in total operational costs, which could be substantial depending on the vessel’s emission levels and the carbon price. The following chart depict how ETS compliance introduces new cost layers on top of traditional fuel expenses.

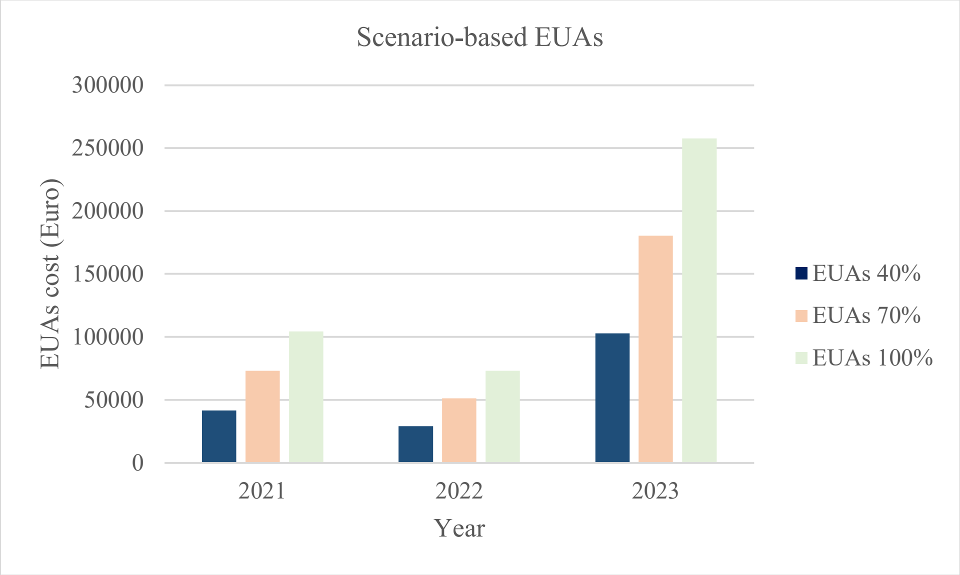


Figure 28: Scenario based EUAs calculation

The chart illustrates the cost of EU allowances based on actual intra- and extra-EU voyages per year, presented in a scenario-based scheme. The chart compares three scenarios: surrendering 40%, 70%, and 100% of EUAs, representing the phased-in approach which is followed by EU. This scenario-based approach allows operators to assess the financial impact of different compliance levels under the EU ETS. The variation between the 40%, 70%, and 100% surrendering scenarios provides insight into how partial compliance compares to full compliance, which includes all emissions from both intra- and extra-EU voyages.

An increase in the number of voyages within the European Union (EU) directly correlates with higher CO_2 emissions, as the operational activity rises. This, in turn, increases the number of EU Allowances (EUAs) that a ship operator is required to surrender under the EU Emissions Trading System (ETS). The greater the emissions, the higher the financial burden on the ship operator, as additional EUAs must be acquired to cover the increased emissions. This exposes ship operator to heightened financial risk and compliance obligations, potentially impacting the overall profitability of operations.

In summary, the final EUAs a ship operator must surrender is a dynamic outcome dependent on the vessel's operational profile within EU, the annual emissions of any GHG under trading scheme, and the prevailing EUA market price, all of which contribute to the total cost of compliance under the EU ETS.

6. Discussion

6.1. Data validation findings and interpretation

The analysis of data entry errors over the years reveals a progressive shift in the nature of reporting inaccuracies. ROB figure errors were the most frequent, signaling significant issues in fuel consumption reporting, likely due to misreporting of fuel types or quantities. While operational events were reported more reliably, fuel data accuracy remained a critical weakness. As improvements were made in fuel data reporting, distance inconsistencies began to surface as the predominant issue, highlighting challenges in accurately capturing voyage distances. Subsequently, the error types became more evenly distributed, with a noticeable increase in event type errors and distance recording.

This progression not only reflects improvements in fuel data management but also suggests that as one aspect of reporting is refined, other areas, such as event reporting and distance tracking, require heightened attention. As operational data validation rules improve, a holistic approach is essential to maintain a trustworthy and reliable database that accurately reflects actual performance.

6.2. Ship operational profile

By examining the vessel's speed profiles, fuel consumption trends, and CO2 emissions over the previous years, improvements driven by regulatory changes can be identified, thus contributing to more sustainable practices in shipping. In the years for which operational data have been analyzed (2021 to 2024), the vessel speeds ranged between 9 and 14 knots, whilst the ship's average speed has shown a consistent decline from 12.8 knots in 2021 to 10.1 knots in 2024. Higher speeds enable the vessel to cover more longer distance, which contributes to a more favorable attained CII. Conversely, extended periods at anchorage had a negative impact on the vessel's operational index, as idle times led to CO_2 emissions without distance traveled. Despite these challenges, the vessel's attained CII falls within the required threshold, ensuring compliance with IMO regulation and proving a competitive energy profile in the market.

The results suggest that operational decision-making and voyage scheduling aimed at minimizing idle time are crucial for CII compliance. Reducing anchorage periods and optimizing sailing speeds improve the ship's CII and its overall operational efficiency. The Blue Visby Solution (BVS), as presented by BIMCO to the IMO Committee

(BIMCO, 2024), further supports these goals by promoting a holistic approach that coordinates port arrivals, reduces idle time, and minimizes fuel consumption.

The BVS aims to address the inefficiencies caused by the "Sail Fast, Then Wait" (SFTW) practice, providing substantial GHG savings from the existing fleet in the short term. In the longer term, it seeks to enhance energy efficiency, which will be crucial as the industry shifts towards alternative fuels with lower energy density and higher costs than traditional marine fuel oil. Importantly, BVS advocates for viewing the fleet as a whole interconnected system rather than optimizing individual vessels in isolation. This system-wide approach offers additional benefits, such as improved anchorage safety by reducing congestion, decreased underwater radiated noise, and lower risk of whale strikes, all of which contribute to a more sustainable and environmentally responsible maritime sector.

6.3. Focus on energy efficiency

The main engine, as the vessel's primary fuel consumer, underscores the importance of real-time performance monitoring and reliable energy efficiency measures. Key interventions include proactive hull and propeller maintenance and continuous performance tracking to ensure optimal operational efficiency. These measures are vital for maintaining the ship's performance within acceptable technological limits, minimizing drag, and optimizing fuel consumption. Regular maintenance not only improves fuel efficiency but also reduces the vessel's CO2 emissions, supporting compliance with current regulatory requirements.

Looking toward the future, alternative fuels with lower carbon intensity, such as biofuels and e-methanol inter alia, must be introduced through pilot projects. These fuels will play a pivotal role in enabling vessels to meet increasingly stringent carbon emission regulations. Transitioning to alternative fuels is essential for long-term compliance, and pilot projects offer valuable learning opportunities for operators to gradually adapt without compromising current operations

As regards the operational energy efficiency solutions, the auxiliary engines present additional opportunities for energy efficiency improvements, particularly during port stays. By reducing unnecessary operating hours and balancing engine loads ship operators can achieve notable CO2 emissions reductions. Efficient auxiliary engine management reduces emissions and operational costs, contributing to overall sustainability and profitability.

Finally, the implementation of a robust carbon management system is imperative, not only for managing emissions today but also for preparing for future technologies capable of achieving net-zero emissions (e.g. carbon capture and storage). Operators must be prepared to adapt to these technologies as they become commercially viable. Early adoption of comprehensive carbon management practices will position operators to remain compliant with evolving regulations, and ensure readiness for more advanced solutions, safeguarding ships' operational and environmental performance in the long term.

In summary, proactive maintenance, alternative fuel adoption, operational optimization, and carbon management systems are all integral to sustaining energy efficiency and ensuring future compliance in a rapidly evolving regulatory landscape.

6.4. EU ETS impact at ship level

The analysis of the cost of EU Allowances (EUAs) based on actual intra- and extra-EU voyages, presented through a scenario-based approach in this work, highlights the financial implications of varying compliance levels under the EU ETS. The results demonstrate that partial compliance, 40% or 70%, provides a more cost-effective option in the short term, however, full compliance 100%, which includes emissions from all intra- and extra-EU voyages, represents the actual future regulatory requirement.

The final amount of EUAs that must be surrendered is subject to:

- The operational profile of voyages to/from EEA countries
- The vessel's fuel efficiency, directly influencing CO_2 emissions
- The prevailing market price of EUA, which fluctuates significantly

The results underscore the importance of implementing strategic planning for EU ETS compliance, as operational and fuel efficiency decisions will have direct implications on the financial burden imposed by the system. To remain compliant and competitive under increasingly stringent regulations, ship operators must be proactive in balancing their compliance costs (i.e. EUA exposure) with operational efficiency, while also preparing for full-scale compliance in the future. Long-term sustainability strategies in the shipping industry must adopt a holistic approach that balances cost, regulatory compliance, and environmental impact.

7. Conclusion

This work implemented a systematic methodology to calculate operational and financial metrics by leveraging real data from ship operation. The process emphasized the importance of iterative data validation to ensure the reliability and accuracy of the dataset, forming the foundation for subsequent analyses. Key operational parameters, including vessel speed, idle times, and the Carbon Intensity Indicator (CII), were calculated, while emissions quantification based on fuel consumption provided a basis for determining the EU allowances required under the EU ETS framework.

The findings highlight that optimizing operational practices, such as minimizing idle time and adopting systematic voyage planning, significantly improves CII performance and operational efficiency. Solutions like the Blue Visby Solution (BVS) further support these goals by reducing inefficiencies, while transitioning to alternative fuels such as biofuels and e-methanol is crucial for long-term compliance with decarbonization goals.

Strategic planning is paramount in addressing the financial implications introduced by the EU ETS. The dynamic interplay between operational profiles, fuel efficiency, and the fluctuating market price of EU Allowances (EUAs) necessitates a comprehensive and data-driven approach to decision-making. Validated and accurate data are critical for calculating emissions, evaluating compliance options, and optimizing operational strategies to minimize exposure to financial risks. Such an approach mitigates financial burdens and ensures long-term competitiveness while advancing the sustainability goals of the maritime sector.

With the overlapping and evolving nature of environmental regulations such as FuelEU Maritime, the EU ETS, and IMO's CII requirements, the need for a comprehensive carbon management system has become evident. Such a system would allow operators to monitor, track, and manage emissions data effectively, ensuring that vessels remain compliant with multiple regulatory frameworks simultaneously. A centralized carbon management platform would also enable ship operators to forecast future emission trends and identify areas for improvement in fuel efficiency. The ability to forecast and plan for these changes will be crucial for maintaining operational and environmental performance in the long term.

Achieving long-term sustainability and regulatory compliance in the maritime sector requires a collaborative approach among ship operators, fuel suppliers, regulatory bodies, and technology providers. Partnerships that focus on shared solutions for fuel infrastructure development, energy-efficient technologies, and low-carbon fuel supply chains are essential to meeting the demands of both FuelEU Maritime and the EU ETS. Successful collaboration between IMO and key stakeholders will play a pivotal role in accelerating the industry's transition toward sustainability. By fostering cooperation across the industry, ship operators can gain access to the resources, knowledge, and technologies needed to optimize operations and remain competitive in a regulatory environment that increasingly prioritizes carbon reduction.

8. References

Adland, R., Cariou, P., Jia, H., & Wolff, F. C. (2018). The energy efficiency effects of periodic ship hull cleaning. *Journal of Cleaner Production*, *178*, 1–13. https://doi.org/10.1016/j.jclepro.2017.12.247

BIMCO. (2024). *GHG emissions reductions through mitigating the operational and commercial practice of Sail Fast Then Wait*. https://www.bimco.org/insights-and-information/safety-security-environment/20241007-sftw-paper

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, *14*(8), 593–598. https://doi.org/10.1016/j.trd.2009.08.005

Deka, T. J., Osman, A. I., Baruah, D. C., & Rooney, D. W. (2022). Methanol fuel production, utilization, and techno-economy: a review. *Environmental Chemistry Letters*, *20*(6), 3525–3554. https://doi.org/10.1007/s10311-022-01485-y

DNV. (2023). *Clarifications on the IMO DCS/CII and EU MRV/ETS, use of biofuel*. www.dnv.com/maritime

E-ferry. (2015). *Ellen – The world's most powerful fully-electric ferry*. https://e-ferryproject.eu/

Energy Observer. (2017). *Compagnie Maritime Belge (Hydroville)*. https://www.energy-observer.org/partners/compagnie-maritime-belge

EU. (2015). Regulation (EU) 2015/757 of the European Parliament and of the Council - of 29 April 2015 - on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union*.

EU. (2023). Directive of the EU Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system. *Official Journal of the European Union*. https://data.consilium.europa.eu/doc/document/PE-9-2023-INIT/en/pdf

European Commission. (2023). *EU ETS Handbook*. https://climate.ec.europa.eu/system/files/2017-03/ets_handbook_en.pdf

Flodén, J., Zetterberg, L., Christodoulou, A., Parsmo, R., Fridell, E., Hansson, J., Rootzén, J., & Woxenius, J. (2024). Shipping in the EU emissions trading system: implications for mitigation, costs and modal split. *Climate Policy*. https://doi.org/10.1080/14693062.2024.2309167

ICCT. (2017). *International Council on Clean Transportation Annual Report 2017*. https://theicct.org/sites/default/files/ICCT_Annual_Report_2017_final.pdf

ICS. (2015). *Shipping and world trade: Driving prosperity*. International Chamber of Shipping. https://www.ics-shipping.org/shipping-fact/shipping-and-world-trade

IEA. (2022). CO2 Emissions in 2022. In *International Energy Agency*. https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO2Emissionsin2022.pdf

IMO. (2020). *Fourth IMO GHG Study 2020: Full Report*. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

IMO. (2022). *Low Carbon GIA Roundtable explores opportunities and challenges of Wind Propulsion Technology*. https://doi.org/https://greenvoyage2050.imo.org/low-carbon-gia-roundtable-explores-opportunities-and-challenges-of-wind-propulsion-technology/

MEPC 62. (2011). Resolution MEPC.203(62): Guidelines on the method of calculation of the Energy Efficiency Design Index for new ships. In *International Maritime Organization*. https://www.imo.org/en/MediaCentre/SecretaryGeneral/Pages/MEPC-62.aspx

MEPC 72. (2018). *Resolution MEPC.304(72): Initial IMO Strategy on Reduction of GHG Emissions from Ships*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/ResolutionMEPC.304(72)_E.pdf

MEPC 75. (2020). *Resolution MEPC.324(75): Amendments to MARPOL Annex VI (Procedures for sampling and verification of the sulphur content of fuel oil and the Energy Efficiency Design Index (EEDI))*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.324(75).pdf

MEPC 76. (2021). *Resolution MEPC.339(76): 2021 Guidelines on the Operational Carbon Intensity Rating of Ships (CII Rating Guidelines, G4)*. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.339(76).pdf

MEPC 80. (2023). *Resolution MEPC.377(80): 2023 IMO Strategy on Reduction of GHG Emissions from Ships*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf

MEPC 82. (2024). *Proposals on candidate mid-term GHG reduction measures* . https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-82nd-session.aspx

MMMCZCS. (2022). Maritime Decarbonization Strategy 2022. In *Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping*. https://cms.zerocarbonshipping.com/media/uploads/publications/Maritime-Decarbonization-Strategy-2022.pdf

MMMCZCS. (2023a). *Technical solutions for the shipping industry to meet IMO's 2030 target*. https://www.zerocarbonshipping.com/news/technical-solutions-for-the-shipping-industry-to-meet-imos-2030-target/

MMMCZCS. (2023b). *The role of energy efficiency regulations*. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. https://doi.org/https://www.zerocarbonshipping.com/publications/the-role-of-energy-efficiency-regulations/

Nelissen, D., Kleijn, A., Delft, D. H., & Delft C.E. (2023). *CII and EU maritime decarbonisation*. www.cedelft.eu

Psaraftis, H. N., Zis, T., & Lagouvardou, S. (2021). A comparative evaluation of market based measures for shipping decarbonization. *Maritime Transport Research*, *2*. https://doi.org/10.1016/j.martra.2021.100019

Ramsay, W., Fridell, E., & Michan, M. (2023). Maritime Energy Transition: Future Fuels and Future Emissions. In *Journal of Marine Science and Application* (Vol. 22, Issue 4, pp. 681–692). Editorial Board of Journal of Harbin Engineering. https://doi.org/10.1007/s11804-023-00369-z

Reddy, V. J., Hariram, N. P., Maity, R., Ghazali, M. F., & Kumarasamy, S. (2023). Sustainable E-Fuels: Green Hydrogen, Methanol and Ammonia for Carbon-Neutral Transportation. *World Electric Vehicle Journal*, *14*(12). https://doi.org/10.3390/wevj14120349

Talluri, L., Nalianda, D. K., & Giuliani, E. (2018). Techno economic and environmental assessment of Flettner rotors for marine propulsion. *Ocean Engineering*, *154*, 1–15. https://doi.org/10.1016/j.oceaneng.2018.02.020

The Fjords. (2018). *Future of the Fjords*. https://www.thefjords.no/fleet/future-of-the-fjords/

UNCTAD. (2023). Review of Maritime Transport 2023. In *United Nations COnference on Trade and Development*. https://unctad.org/system/files/official-document/rmt2023_en.pdf

Wang, S., Zhen, L., Psaraftis, H. N., & Yan, R. (2021). Implications of the EU's Inclusion of Maritime Transport in the Emissions Trading System for Shipping Companies. *Engineering*, *7*(5), 554–557. https://doi.org/10.1016/j.eng.2021.01.007

9. Annex I

imo	date_utc	time_utc	voy_from	voy_to	lat_deg	lat_min	lat_n_s	lon_deg	lon_min	lon_e_w	wind_bft	event
9700002	5/2/2023	15:50	ESTAR	GIGIB	36	8	N	5	22	W	0	NOON
9700002	5/2/2023	17:15	GIGIB	ESBIO	36	8	N	5	21	W	3	DEPARTURE
9700002	6/2/2023	13:00	GIGIB	ESBIO	37	15	N	9	27	W	3	NOON
9700002	7/2/2023	13:00	GIGIB	ESBIO	41	56	N	9	48	W	5	NOON
9700002	8/2/2023	13:00	GIGIB	ESBIO	43	53	N	7	12	W	6	NOON
9700002	9/2/2023	8:00	GIGIB	ESBIO	43	17	N	2	55	W	4	NOON
9700002	9/2/2023	11:00	GIGIB	ESBIO	43	38	N	4	12	W	3	NOON
9700002	10/2/2023	11:00	GIGIB	ESBIO	43	42	N	4	14	W	0	NOON
9700002	11/2/2023	11:00	GIGIB	ESBIO	43	39	N	4	14	W	2	NOON
9700002	12/2/2023	0:00	GIGIB	ESBIO	43	17	N	2	55	W	0	ARRIVAL

distance	cargo_mt	me_cons_hfo	me_cons_lfo	me_cons_mgo	ae_cons_hfo	ae_cons_lfo	ae_cons_mgo	hfo_rob	lfo_rob	mgo_rob
0	0	0	0	0	0	0	0.4	450	0	20.5
3	0	0.2	0	0	0.1	0	0	449.7	0	20.5
230	0	10.2	0	0	2	0	0	437.5	0	20.5
284	0	13	0	0	2.5	0	0	422	0	20.5
201	0	13	0	0	2.5	0	0	406.5	0	20.5
122	0	4.1	0	0	2.5	0	0	399.5	0	20.5
15	0	0.3	0	0	0.3	0	0	398.8	0	20.5
37	0	1.4	0	0	2.5	0	0	393.9	0	20.5
40	0	1.3	0	0	2.5	0	0	389.1	0	20.5
68	0	2.4	0	0	1	0	0	385.2	0	20.5

Table 5: Part of raw data from noon reports

10.Annex II: Python coding program

This annex presents excerpts from the Python scripts developed to perform key calculations for this study. It serves as a reference for the methodological framework and technical reproducibility of the analysis.

```
import pandas as pd

import numpy as np

folder = r'C:\Users\user\Desktop\noon reports data'

csv_files = glob.glob(os.path.join(folder, "*.csv"))

…

dataframes = [pd.read_csv(file, usecols=range(num_fields)) for file in csv_files]

def separate_voyages_and_ports(df):

    for i in range(len(df)):

          if df.loc[i,'event'] == 'NOON':

            fc_hfo_cnt += df.loc[i, 'me_cons_hfo'] + df.loc[i, 'ae_cons_hfo']

            fc_lfo_cnt += df.loc[i, 'me_cons_lfo'] + df.loc[i, 'ae_conson_lfo']

            dist_cnt += df.loc[i, 'distance']

…

def calculate_cii_ref(row):

    if row['VESSEL TYPE'] == 'Container':

        a, c = 1984, 0.489

    elif row['VESSEL TYPE'] == 'Bulk':

        a, c = 4745, 0.622

    return a * (row['SUMMER DWT'] ** -c)
```