UNIVERSITY OF PIRAEUS

ΣΧΟΛΗ ΒΙΟΜΗΧΑΝΙΑΣ ΚΑΙ ΝΑΥΤΙΛΙΑΣ
ΤΜΗΜΑ ΝΑΥΤΙΛΙΑΚΩΝ ΣΠΟΥΔΩΝ

ΣΧΟΛΗ ΝΑΥΤΙΚΩΝ ΔΟΚΙΜΩΝ
ΤΜΗΜΑ ΝΑΥΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ

DEPARTMENT OF MARITIME STUDIES

M.SC. in Marine Science and Technology Management

CARBON PRICING OPTIONS FOR MARITIME EMISSIONS

Maria Karyoti - mnsnd 21021

Master Thesis

submitted to the Department of Maritime Studies of the University of Piraeus as part of the requirements for obtaining the Postgraduate Specialization Diploma in “Marine Science and Technology Management”

Piraeus,

July 2023

DECLARATION OF AUTHENTICITY / COPYRIGHT ISSUES

The person preparing the Thesis bears the entire responsibility of determining the fair use of the material, which is defined on the basis of the following factors: the purpose and character of the use (commercial, non-profit or educational), the nature of the material used (part of the text, tables, figures, images or maps), the rate and importance of its possible consequences on the market, or the general value of the copyrighted text.

The present Thesis was unanimously approved by the Three-member Examination Committee appointed by the Specific Joint Committee (ΕΔιΕ) of the M.Sc. in accordance with the Operating Regulations of the M.Sc. “Marine Science and Technology Management”. The members of the Committee were:

- Associate Professor Dr. Pariotis Efthimios (Supervisor)
- Associate Professor Dr. Katsanis John
- Associate Professor Dr. Zannis Theodoros

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

"With heartfelt gratitude and deep appreciation, I dedicate this paper to all those who have played a significant role in its creation.

To my esteemed professor, your guidance and encouragement have fueled my determination and inspired me to reach new heights. Your expertise and mentorship have been invaluable throughout this journey.

To my cherished family, your unwavering support and encouragement have been a constant source of strength throughout this journey.

To my dear friends and colleagues, I am incredibly grateful for your friendship, collaboration, and the insightful discussions we have shared. Your presence has made this academic pursuit more meaningful and memorable. Thank you for making it easier for me to navigate this journey.

Thank you all for being an integral part of this journey. Without your support, this achievement would not have been possible."

ABSTRACT

This research thoroughly examines the potential and implications of diverse carbon pricing strategies within the maritime shipping industry, a sector significantly contributing to global CO_2 emissions. Considering the international scope of shipping, establishing a globally recognized and consistent carbon pricing mechanism poses numerous challenges, yet offers considerable opportunities. This paper navigates through the existing regulatory framework, recently adopted regulations and proposals, as well as prospective market-based mechanisms, providing an analysis of their unique features and mutual disparities.

In-depth insight is drawn around the newly introduced EU Emissions Trading Scheme and the FuelEU maritime regulation, both implemented by the EU – a prominent regional policymaker. The study scrutinizes various dimensions of these MBMs and their consequential impacts on the maritime industry, as well as referencing the experiences of these mechanisms within other sectors and geographic jurisdictions. Further considerations are also raised around determining carbon price levels, identifying who bears the cost burden, and understanding the generation of new revenue streams.

Findings suggest that although no singular solution is universally applicable, a well-structured carbon pricing mechanism possesses the potential to not only decrease emissions but also incentivize technological advancement and efficiency within the shipping sector. The research stresses the imperative need for international cooperation and stringent regulation to guarantee the effectiveness of such a scheme.

By contributing to the emerging knowledge base surrounding the role of MBMs in decarbonizing the global shipping sector, this research serves as a valuable resource for various stakeholders in the maritime industry. It assists in better understanding the potential of various MBMs for shipping and provides guidance in transitioning towards sustainable strategies.

Key words

GHG, MBMs, EU ETS, FuelEU, MACCs, Cap-and-trade, Carbon Tax, Levy, EU MRV, Well-to-wake, Carbon Intensity

TABLE OF CONTENTS

TABLE OF FIGURES

ABBREVIATIONS

CO_2: carbon dioxide

SO_x: Sulphur Oxides

NO_x: Nitrogen Oxides

GHG: Greenhouse Gas

UNFCCC: United Nations Framework Convention on Climate Change

IMO: International Maritime Organization

N_2O: Nitrous Oxide

CH_4: Methane

ECAs: Emission Control Areas

MARPOL: International Convention for the Prevention of Pollution from Ships

MEPC: Marine Environment Protection Committee

LCA: Life Cycle Assessment

SEEMP: Ship Energy Efficiency Management Plan

EEDI: Energy Efficiency Design Index

EEXI: Energy Efficiency Existing Ship Index

CII: Carbon Intensity Indicator

GT: Gross Tonnage

EU: European Union

ETS: Emissions Trading System

AMP: Alternative Maritime Power

OCC: Onboard Carbon Capture

CCS: Carbon Capture and Storage

LNG: Liquefied Natural Gas

MSC: Mediterranean Shipping Company

MBMs: Market-Based Measures

ETS: International shipping Emission Trading System

SIDS: Small Island Developing States

LDCs: Least Developed Countries

MRV: Monitoring, Reporting, and Verifying

DoC: Document of Compliance

IMO DCS: International Maritime Organization's Data Collection System

CBAM: Carbon Border Adjustment Mechanism

MAC: Marginal Abatement Cost

TCPs: Time Charter Parties

MACCs: Marginal Abatement Cost Curves

EU ETS: European Union Emissions Trading System

EEA: European Economic Area

OPS: Onshore Power Supply

EUA: European Union Allowances

LCA: Lifecycle Assessment

F&R: Fund and Reward

SCC: Reflecting the Social Cost of Carbon

1 INTRODUCTION

Climate change, specifically the aspect of global warming, is one of the most significant and urgent environmental dilemmas confronting our planet at present. These phenomena are predominantly fueled by the escalating levels of greenhouse gases in our atmosphere, a result of human-induced activities that include the combustion of fossil fuels, rampant deforestation, and various industrial processes.

This escalation in greenhouse gases instigates a rise in the Earth's average temperature, a phenomenon commonly referred to as global warming. The increase in global temperature can provoke a series of adverse effects on our environment, including rising sea levels, an augmented frequency of extreme weather events, and altered precipitation patterns. These environmental shifts can have severe repercussions on food production and water resources, adversely affecting human societies and economies on a global scale. The impacts of climate change and global warming are felt universally, resulting in substantial economic, social, and environmental consequences.

Given the wide-ranging implications and the grave nature of these issues, it is essential to take decisive action. Strategies for mitigation can span a spectrum of measures, such as reducing greenhouse gas emissions, transitioning to renewable energy sources, and the adoption of sustainable practices (Intergovernmental Panel on Climate Change, 2022).

1.1 DEMAND FOR DECARBONIZATION IN SHIPPING INDUSTRY

The shipping industry is a critical pillar of the global economy, orchestrating the transfer of goods, people, and facilitating intercontinental trade. Its reach extends to over 50,000 merchant ships registered across more than 150 nations, operated by a million seafarers of varying nationalities. This vast fleet conveys almost 90% of the world's trade, underscoring its indispensable role in global commerce. Over the past century, the total trade volume has escalated due to industrialization, economic growth, and technological advancements, thus resulting in a quadrupling of seaborne trade estimates over the past four decades (ICS, 2023) (IMO, 2020).

However, this crucial industry presents a considerable environmental challenge. According to the *Fourth IMO Greenhouse Gas Study 2020* (IMO, 2020), the shipping sector accounts for approximately 2.2% of global Greenhouse Gas (GHG) emissions. Worryingly, if no preventative measures are undertaken, these emissions could climb up to 250% by 2050, exacerbating global warming and counteracting the objectives of the Paris Agreement (1.3.2) (Figure 1) (UNFCCC, 2018) (Lind & Lehmacher, 2022).

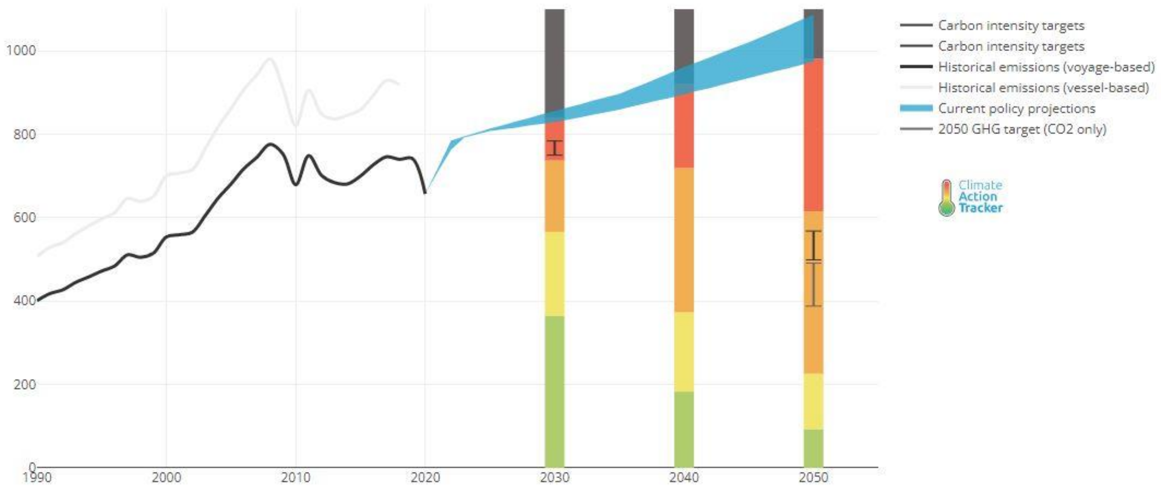

Figure 1

Carbon Intensity projections and targets by (Climate Analytics and NewClimate Institute, 2021)

The industry's dependence on heavy fuel oil, a significant source of carbon dioxide (CO_2), sulphur oxides (SO_x), and nitrogen oxides (NO_x) emissions, contributes to climate change and negatively impacts human health and the environment.

In light of these challenges, the shipping industry faces increasing pressure from customers, governments, and society to reduce its carbon footprint. Many companies are setting their own emissions reduction targets and seeking shipping partners who can help them meet these objectives. This has spurred the emergence of "green shipping" initiatives, where shipping companies adopt more sustainable practices and use low-carbon fuels to meet the growing demand for decarbonized shipping (Hessevik, 2022).

The roadmap to decarbonization necessitates significant changes in the industry, including the development and adoption of new technologies such as alternative fuels like hydrogen or ammonia, increased energy efficiency, and operational adjustments. Despite the high costs and technical complexity, industries are embracing this transition due to its potential benefits for the environment and long-term economic viability (Helmi, 2021).

Regulatory bodies and policymakers must support the shipping industry in its decarbonization efforts. This includes fostering international policies that facilitate global regulatory convergence and harmonization. Cooperation between regulators and industry leaders is essential to ensuring a balance between environmental preservation and the requirements of the private sector.

Meanwhile, consumers and businesses must rethink their sourcing strategies to further reduce CO_2 emissions associated with the shipping/logistics industries. Embracing local sourcing not only efficiently reduces carbon emissions but also bolsters local economies.

Decarbonization will be primarily reliant on green fuels, while digital technology plays a role in boosting energy efficiency. As solar and wind farms expand to produce more green hydrogen, costs should decline, allowing for almost limitless shipping carbon emission reductions (Helmi, 2021). Moreover, digital innovations, like GHG emissions calculators, digital twins of engines, ships, and port infrastructure, can foster collaborative innovation and knowledge sharing across the industry (Lind & Lehmacher, 2022).

The first step is to create co-ownership of the problem by identifying and defining a shared interest among the people involved (Lind & Lehmacher, 2022). Decarbonizing shipping through the three value chains of fuel, ship and operations is the common thread. The ultimate objective is to have a zero-emissions marine sector (Figure 2) (UNCTAD, 2022).

In summary, addressing the environmental impact of the shipping industry is both a global responsibility and an opportunity. Achieving a balance between the necessity of global commerce and the urgency of environmental preservation requires a concerted effort from all stakeholders. The path to decarbonization is challenging but crucial for the sustainability of the shipping industry and, by extension, the global economy.

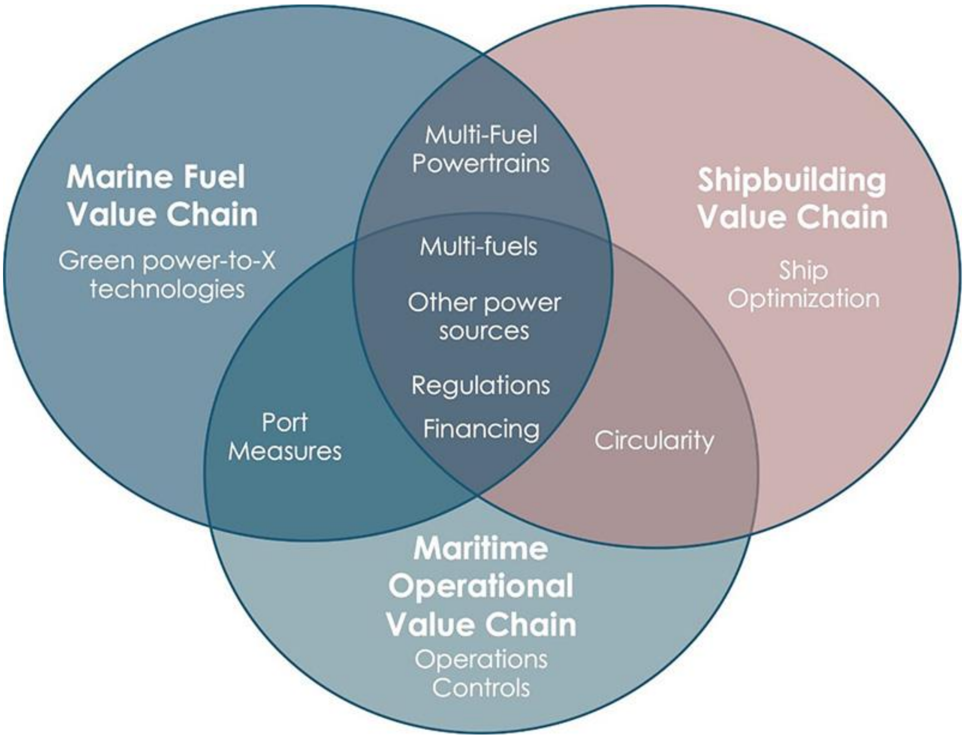

Figure 2

Value chains and selected decarbonization enablers (Source and illustration: (Lind & Lehmacher, 2022))

1.2 AIR POLLUTANTS AND GREENHOUSE GASES

Emissions from ships contribute significantly to global air pollution, posing substantial threats to climate, air quality, human health, and the broader environment. Each year, air pollution is implicated in approximately 6.5 million deaths globally, with the shipping industry linked to an estimated 250,000 premature deaths and 6.4 million cases of childhood asthma. A significant proportion of these emissions occur near populated coastal regions, exacerbating air quality issues along coastlines, with roughly 70% of ship emissions released within 400 km of shorelines.

The shipping industry contributes considerably to global anthropogenic emissions of nitrogen oxide and sulphur oxide, accounting for around 15% and 13% respectively (Stefan

Gössling, 2021). Regional variations exist for PM2.5[1] particulate emissions from ships, with proportions ranging from 7% in Africa to 22% in Oceania.

Ship emissions encompass products from both complete and incomplete combustion of fuel. Complete combustion results in emissions like CO_2 and SO_x, while incomplete combustion leads to emissions including hydrocarbons (such as methane), carbon monoxide, and particulate matter. The by-products of exhaust after-treatment systems include pollutants such as nitrogen dioxide, ammonia, and nitrous oxide (N_2O). Heavy metal emissions are derived from fuel, lubricating oil, and engine wear. SO_x and NO_x emissions have damaging environmental impacts, contributing to acid rain and water eutrophication. Furthermore, ships, particularly in ports, contribute significantly to total NO_x emissions, leading to high NO_x concentrations in proximate communities and city centers.

Overlooked pollutants, such as methane (CH_4) and nitrous oxide, carry significant environmental implications. Methane contributes to tropospheric ozone formation in regions dominated by background methane, while N_2O depletes stratospheric ozone. These emissions could intensify with the potential introduction of ammonia as marine fuel and the use of exhaust after-treatment technologies that include N_2O emissions, which must be managed effectively.

Regulations by the International Maritime Organization seek to control SO_x and NO_x emissions from ships, with additional rules expected to be introduced for black carbon and methane emissions (Päivi T. Aakko-Saksa, 2023). The regulation on sulphur oxides emissions, known as IMO 2020, became effective on January 1st, 2020, imposing a maximum sulphur cap of 0.5% in marine fuels, significantly reduced from the 4.5% to 3.5% limit as of 2012 (IMO, 2019). To comply, ships may switch to low-sulphur fuels, alternative fuels like Liquefied Natural Gas (LNG), or utilize exhaust gas cleaning systems – also known as scrubbers – to remove pollutants from their emissions (Figure 3).

---

[1] Particulate matter is a composite of solid and liquid particles that can be emitted directly or be created when pollutants from various sources react in the atmosphere. The sizes of particulate matter vary, but particles smaller than 10 micrometers are of particular concern as they lead to severe health issues.

PM10 refers to particulate matter with a diameter less than 10 micrometers. PM2.5, also known as fine particles, denotes particulate matter with a diameter less than 2.5 micrometers. To defining their standards, both the EU and the World Health Organization take into account the total mass of PM10 and PM2.5 (European Environment Agency, 2023).

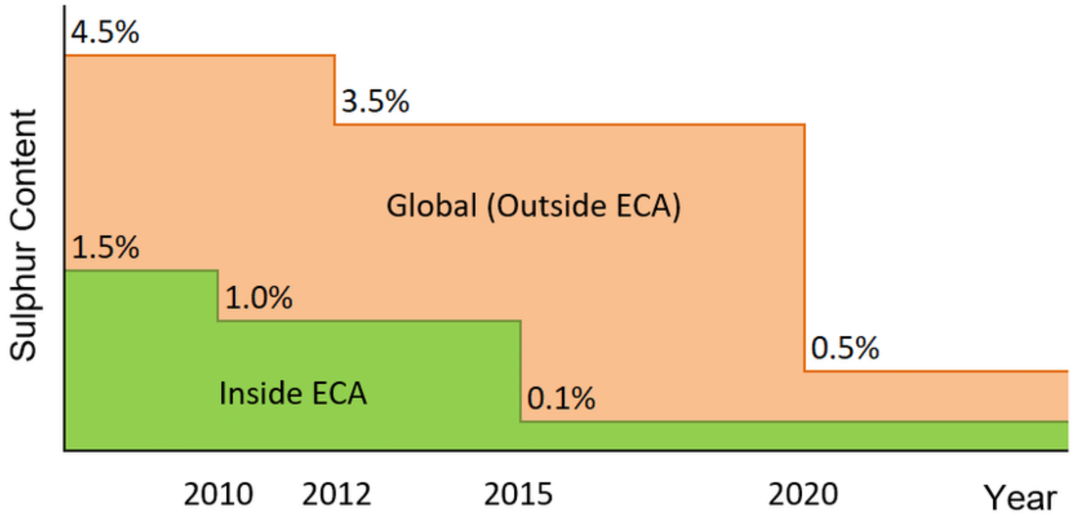

Figure 3

IMO Sulphur Regulation (MARPOL Annex VI Reg. 14)

Additionally, the IMO has established regional Emission Control Areas (ECAs) for SO_x and NO_x. Ships operating in ECAs, regions identified for their ecological sensitivity or proximity to populated zones, are required to use fuels with a maximum sulphur content of 0.10%, as opposed to the 0.50% sulphur content limit applicable globally under IMO 2020. Ships that fail to comply with ECA sulphur limits can face penalties and fines. Moreover, a standard on NO_x emissions, known as Tier III, is in place by the IMO, requiring ships operating in designated ECAs to reduce their NO_x emissions by 75% compared to previous Tier II standards.

On the greenhouse gas front, the shipping industry leaves an extensive carbon footprint[2], primarily comprising CO_2, but also including potent greenhouse gases like methane and nitrous oxide. To holistically gauge the environmental impact of the shipping industry, it's

[2] A carbon footprint encompasses the aggregate greenhouse gas (GHG) emissions produced directly or indirectly by an individual, organization, event, or product (The Hong Kong Polytechnic University, 2013). This collective emission is quantified in terms of carbon dioxide equivalent (CO_2-e). A comprehensive carbon footprint considers all six GHG emissions specified in the Kyoto Protocol, namely:

1. Carbon Dioxide (CO_2)
2. Methane (CH_4)
3. Nitrous Oxide (N_2O)
4. Hydrofluorocarbons (HFCs)
5. Perfluorocarbons (PFCs)
6. Sulphur Hexafluoride (SF_6)

essential to consider not only the volume of CO_2 emissions, but also the aggregate GHG emissions, given their varying global warming potentials. Here, the concept of carbon dioxide equivalent (CO_2eq), which quantifies the warming impact of each greenhouse gas in terms of CO_2, is pivotal (Figure 4). Employing the CO_2eq measure offers a comprehensive view of the shipping industry's role in climate change, thereby assisting in formulating effective policies and strategies to mitigate the climate impact of shipping, setting industry-wide emissions reduction targets and tracking progress towards these goals. Recognizing the full scale of the industry's GHG emissions in terms of CO_2eq is a significant step towards a more sustainable and environmentally responsible future for global trade and transportation.

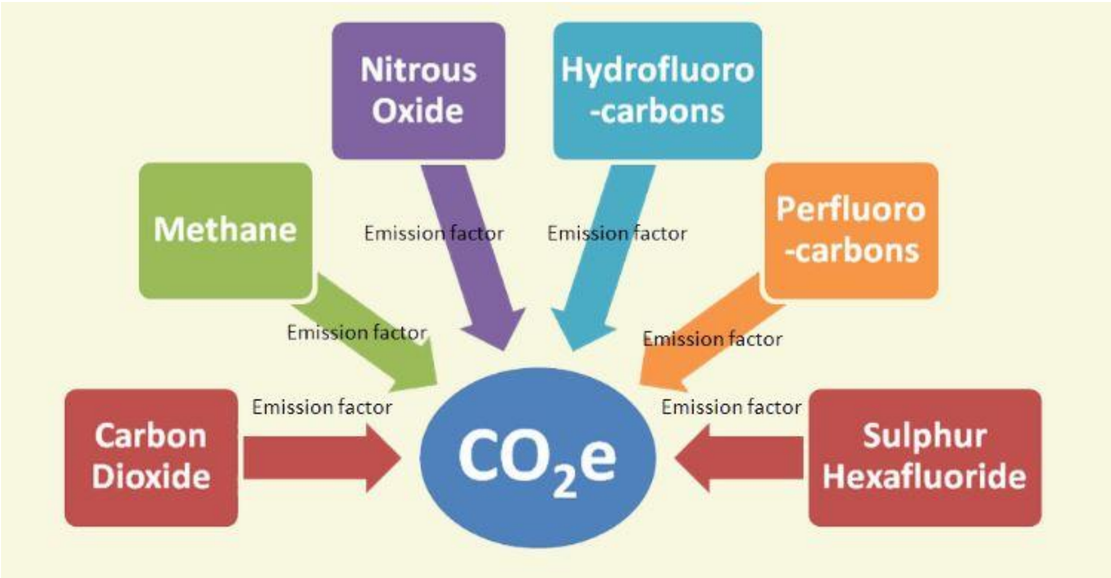

Figure 4

Greenhouse gases and CO_2eq (The Hong Kong Polytechnic University, 2013)

1.3 THE PATH TO CURRENT FRAMEWORK

1.3.1 The Kyoto Protocol, 1997

The Kyoto Protocol is the first legally binding treaty that was adopted in 1997 as an extension of the *United Nations Framework Convention on Climate Change*. Its main goal was to address global warming by setting binding targets for reducing greenhouse gas emissions. Specifically, the Kyoto Protocol aimed to:

- Reduce greenhouse gas emissions from industrialized countries by 5.2% below 1990 levels by the end of the first commitment period, which was from 2008-2012. The intention was to slow down the increase of GHG concentrations in the atmosphere and the resulting global warming (United Nations, 2022).
- Create market-based mechanisms to help countries meet their emissions targets. These were emissions trading, joint implementation and the Clean Development Mechanism. These mechanisms allowed countries to trade emissions credits and invest in emissions-reduction projects in other countries to help achieve their emissions targets.
- Encourage sustainable development by helping countries transition to low-carbon economies and investing in clean technologies. The protocol also recognized the importance of preserving and enhancing sinks and reservoirs of greenhouse gases, such as forests and oceans.

The Kyoto Protocol aimed to address global warming by reducing greenhouse gas emissions and promoting sustainable development. Although the protocol has been criticized for not going far enough, it marked a significant milestone as the inaugural multilateral agreement in which several participating nations made commitments to restrict their emissions of greenhouse gases. Additionally, it was notable for introducing market-based mechanisms for the first time (UNFCCC , 2022).

1.3.2 The Paris Agreement, 2015

The Paris Agreement is an international treaty adopted in 2015 by the UNFCCC that aims to address climate change and its impacts. The agreement has several goals, including:

- Limiting global temperature rise to well below 2°C (3.6°F) above pre-industrial levels, while aiming for a limit of 1.5°C (2.7°F).
- Reducing greenhouse gas emissions to achieve the temperature goals. The Paris Agreement sets a long-term goal of net-zero greenhouse gas emissions in the second half of this century. This means that by around 2050, human-caused emissions of CO_2 and other heat-trapping gases must be balanced by removing them from the atmosphere or offsetting them with emissions reductions in other sectors or countries.

- Increasing climate resilience and adaptation. The agreement therefore calls for enhanced adaptation efforts and support for vulnerable countries and communities, particularly in developing countries, to cope with the impacts of climate change, such as sea-level rise, ocean acidification, desertification and loss of biodiversity.
- Mobilizing finance, technology, and capacity-building. To achieve the above goals, the Paris Agreement calls for a collective effort by all countries, developed and developing, to mobilize financial resources, transfer technology and enhance capacity-building, particularly for developing countries, to support their transition to low-carbon, climate-resilient and sustainable development pathways. The agreement aims to raise $100 billion annually by 2020 from public and private sources to support climate action in developing countries, and to enhance transparency and accountability in reporting and reviewing progress towards the goals.

In simple terms, the Paris Agreement is a significant milestone in the global effort to combat climate change, as for the first time, 195 countries have come together to work towards a common goal. The agreement is built on the principles of fairness, shared responsibility, and each country's individual ability to take action. However, the success of the agreement depends on the participation and collaboration of all countries and sectors, including governments, businesses, and individuals, as well as the involvement of civil society and academic institutions.

1.4 Maritime Regulators

1.4.1 International Maritime Organization

The International Maritime Organization is the United Nations’ agency responsible for regulating the shipping industry on a global scale. Established in 1948 and starting operations in 1959, the organization's fundamental objective involves the creation and sustenance of a comprehensive regulatory structure for the shipping industry. This framework covers a multitude of aspects, including safety standards, environmental impact, legal issues, technical cooperation, maritime security, and the overall efficiency of shipping operations.

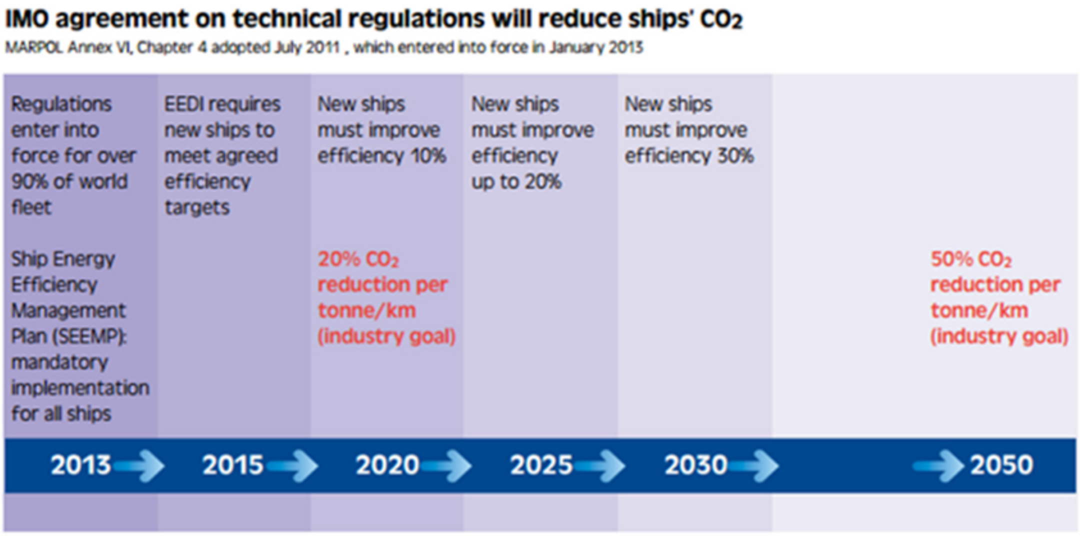

Figure 5

Previous target of IMO plans for decarbonization

One of the IMO's key environmental responsibilities is to control pollution from ships. This is achieved through the International Convention for the Prevention of Pollution from Ships (MARPOL), one of the most important IMO treaties, which addresses pollution from ships from various sources, including oil, noxious liquid substances, harmful substances carried by sea in packaged form, sewage, garbage, and the emission of air pollutants.

In recent years, IMO has been working intensively on measures to reduce greenhouse gas emissions from ships, in line with the Paris Agreement's goals and the UN's Sustainable Development Goals. The IMO adopted an initial strategy on the reduction of greenhouse gas emissions from ships in 2018, outlining a vision to phase out such emissions as soon as possible within this century.

While IMO sets global standards, the implementation and enforcement of these standards are up to the Member States, usually through their national maritime administrations.

The International Maritime Organization is actively working to regulate and reduce emissions from the shipping industry, with a focus on SO_x, NO_x, and GHG emissions, to mitigate the industry's impact on the environment and ensure a more sustainable future.

1.4.1.1 IMO's Initial Strategy on the Reduction of GHG Emissions

The *IMO's Initial GHG Strategy*, adopted in April 2018, outlines a prospective blueprint for the international shipping sector, setting ambitious objectives for lowering greenhouse gas emissions and providing guiding principles. It also puts forth a range of proposed actions, along with potential timelines. Key strategic avenues of the Initial GHG Strategy comprise:

- **Boosting ship energy efficiency:** There's a commitment to implement and enforce regulatory measures and formulate new ones as needed to curtail and minimize greenhouse gas emissions from international shipping, leveraging past successful experiences with technical and operational energy efficiency measures for ships.
- **Promoting technological and infrastructural development:** The strategy aims to foster innovation and offer incentives for research and development in energy-efficient technologies and the utilization of alternative energy sources.
- **Diminishing carbon intensity:** There's an aim to decrease carbon intensity of ships via further implementation phases of the energy efficiency design index for new ships.

The strategy sets out clear levels of ambition for the international shipping sector by reducing its carbon intensity. This includes reducing CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, and striving to reach a 70% reduction by 2050, both compared to 2008 levels. In addition, the total annual GHG emissions from international shipping are set to be diminished by at least 50% by 2050 compared to 2008, while simultaneously pursuing efforts towards phasing out GHG emissions entirely. This full phase-out aligns with the temperature objectives of the Paris Agreement.

To align with the goal of reducing greenhouse gas emissions by 2050, IMO has proactively outlined a sequence of actions to be taken in the short-term (2018-2023), mid-term (2023-2030), and long-term (beyond 2030), which are further analyzed in the following chapters.

In December 2022, the Marine Environment Protection Committee (MEPC[3] 77) deliberated on additional proposals and reaffirmed its pledge to adopt a revised, more robust *IMO*

[3] The Marine Environment Protection Committee (MEPC) is one of the main bodies of the IMO. In the context of greenhouse gas emissions from ships, the MEPC has been the main body within the IMO that has been working on developing and implementing measures to reduce these emissions. This includes the development of the initial IMO GHG Strategy, and the ongoing work to revise this strategy and adopt concrete measures for reducing shipping emissions (IMO, 2019).

Greenhouse Gas Strategy aiming to significantly reduce the maritime industry's carbon footprint in line with global climate change efforts.

During the 80th session of the Marine Environment Protection Committee (MEPC 80) in July 2023, a comprehensive revision of the GHG Strategy was approved. This updated strategy indicates a substantial escalation from the initial objective of achieving a 50% reduction in emissions by 2050. The revised targets aim for a decrease in well-to-wake GHG emissions (3.4.2.1.1) by at least 20% by 2030, with a more ambitious goal of 30%, and a substantial reduction of 70% by 2040, with an aspirational target of 80%. The long-term vision is to achieve net-zero emissions by around 2050. Furthermore, the strategy has outlined an interim target for 2030, encouraging the adoption of technologies, fuels, and energy sources with zero or near-zero GHG emissions. The intent is to see these clean technologies, fuels, and energy sources account for at least 5% and potentially up to 10% of the total energy utilized in international shipping (DNV, 2023).

The revised GHG Strategy has expanded its scope to include life-cycle GHG emissions from shipping, aiming to reduce emissions within the energy system of international shipping and prevent the shift of emissions to other sectors.

To meet these demanding emissions reduction goals, the IMO has proposed a two-part plan. The first part involves a targeted marine fuel standard, designed to oversee the progressive reduction of marine fuel GHG intensity. The second part features a pricing mechanism for maritime GHG emissions, potentially linked directly to the GHG intensity mechanism.

In addition, the MEPC 80 introduced the *Guidelines on Life Cycle GHG Intensity of Marine Fuels*, offering methods to calculate GHG emissions for all fuels and energy carriers used on a ship, from production to consumption. Created to support the GHG Fuel Standard, the guidelines also provide initial default emission factors for various fuels, which are subject to further review.

Furthermore, the MEPC 80 initiated a discussion on the use of on-board carbon capture and storage (2.2.3). However, deeper analysis on this topic was postponed to the next meeting of the Working Group on GHG reductions, slated for April 2024, coinciding with further work on the Life Cycle Assessment (LCA) guidelines.

1.4.1.2 Adopted Actions

Through its *Initial Strategy*, IMO has developed several innovative tools to tackle energy inefficiency and the high carbon footprint associated with maritime operations. These tools include the Ship Energy Efficiency Management Plan (SEEMP), the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII).

The Ship Energy Efficiency Management Plan was introduced by the IMO as an operational measure to assist shipping companies in enhancing their energy utilization and decreasing GHG emissions from ships. The plan offers a systematic approach to improving a vessel's energy efficiency, comprising four main components: planning, implementation, monitoring, and self-evaluation. This operational tool applies to all ships, irrespective of their size or age, and is flexible enough to be tailored to the specific needs of each vessel. As part of their SEEMP, shipping companies are required to outline measures for reducing GHG emissions and enhancing energy efficiency, with specific targets and a timeline for implementation. Upon approval, they must implement these measures and monitor their effectiveness.

The Energy Efficiency Design Index, on the other hand, is a technical measure adopted by the IMO to set a minimum energy efficiency standard for newly built ships based on their carbon intensity. It is computed for each new cargo ship larger than 400 Gross Tonnage (GT) and provides a clear measure of the CO_2 emissions produced by the ship's engine per unit of distance. The value of the EEDI must be lower than a required value set by the IMO, demonstrating the ship's contribution to emission reduction.

The Energy Efficiency Existing Ship Index was conceived to extend the scope of the EEDI to existing ships. It shares EEDI's performance-based framework, setting a baseline for energy efficiency in vessels. EEXI applies to cargo vessels exceeding 400 GT that were constructed before the 2013 EEDI mandate. This particular focus on older, existing vessels reflects the IMO's intent to promote energy efficiency across the entirety of the maritime sector, not just in new ship construction.

In practice, EEXI encourages ship owners to enhance the energy efficiency of their existing fleet. This might be achieved through the retrofitting of ships with newer, more energy-efficient technologies or subsystems. Alternatively, owners might invest in new ships that are designed and built with advanced energy-efficient technologies. By implementing EEXI, IMO motivates ship owners to upgrade their vessels and reduce their environmental impact, thereby contributing to the global effort against climate change. The calculation method for these indices leverages data from a multitude of sources, encompassing both official reports and intricate estimation models. IMO stipulates that a ship's *Attained EEDI/EEXI* value must fall below a specific threshold to be recognized as contributing to emission reductions. Moreover, this requirement has become progressively more stringent since its introduction in 2013, with the requisite values being incrementally decreased over time. With the EEXI regulation coming into effect in January 2023, the coverage of this ruling is expected to expand to encompass virtually all cargo ships.

The Carbon Intensity Indicator is a performance-based measure adopted by the IMO to evaluate the carbon intensity of a ship's operations over a specific period. It considers the volume of carbon emissions produced per transport work, such as per tonne-mile. CII applies to all vessels that are 5,000 GT and above, reflecting the significant role that large ships play in global emissions.

To adhere to the CII, ships must measure and report their carbon emissions relative to their transport work on an annual basis. This data is then used to establish a ranking system that categorizes ships based on their carbon efficiency. A low CII rating signifies a ship that operates with high carbon efficiency, while a high rating indicates the opposite. This rating system encourages ship owners and operators to reduce the carbon intensity of their operations, incentivizing the adoption of lower-carbon and more sustainable shipping practices.

In essence, EEXI and CII are transformative tools developed by the IMO to drive the maritime sector towards greater energy efficiency and a reduced carbon footprint. They provide a clear framework for ships, both old and new, to align their operations with the global agenda of reducing greenhouse gas emissions and combating climate change.

Lastly, IMO has adopted CII as a performance-based indicator to measure the carbon intensity of a ship's operations, which considers the amount of carbon emissions produced per transport work, such as tonne-mile, over a specific period. It applies to all ships that are 5,000 GT and above. Ships are required to measure and report their carbon emissions per transport work annually. This data contributes to a rating scheme that ranks ships according to their carbon efficiency, encouraging ship owners and operators to reduce the carbon intensity of their operations.

The effective application of these tools, SEEMP, EEDI, EEXI, and CII, reflects the shipping industry's commitment to energy efficiency and emission reduction, and they constitute a fundamental part of the industry's strategy to mitigate its environmental impact. All these measures are being closely scrutinized by ship owners, charterers, and other stakeholders, and IMO continues to work on defining the consequences for non-compliance, a crucial aspect for the effectiveness of these measures in achieving a sustainable shipping industry.

1.4.2 EU Fit for 55

In addition to international regulations, some regional authorities have implemented their own decarbonization regulations for shipping within their waters. The European Union (EU) has set a target to reduce GHG emissions from the shipping industry by at least 40% by 2030, compared to 1990 levels.

The *Fit for 55* package is a comprehensive set of legislative measures adopted by the European Commission on July 14th, 2021. It aims to reduce the European Union's net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. This ambitious plan is part of the broader European Green Deal, which seeks to achieve climate neutrality by 2050. The package contains several key elements that target various sectors of the economy, including energy, transport, buildings, and industry. Some of the main proposals include (European Commission, 2023):

- Extending the EU ETS to maritime transport, which would cap maritime transport emissions as part of the overall ETS cap, establish a signal for the price of carbon that would encourage flexible and economical GHG emission reduction, generate funds to combat climate change, and promote innovation.
- Increasing the demand for marine renewable and low-carbon fuels through the establishment of a maximum cap on the amount of energy used by ships calling at European ports, as well as the promotion of zero-emission technology at berth using a technology-neutral strategy.
- Addressing the risk of carbon leakage, which occurs when companies move their operations to countries with lower emissions standards to avoid the cost of complying with the ETS. This can be done by providing free allowances or other measures to industries that are at risk of carbon leakage.

- Expanding alternative fuel infrastructures, which would establish requirements for shore-side electrical supply at inland and maritime ports, among other things.
- Increasing the EU's present aim of at least 32% of renewable energy sources in the overall energy mix to at least 40% by 2030, with a focus on sectors where growth has been slower thus far, such as transportation, will accelerate the supply of renewables in the EU.
- Revision of the current Energy Taxation Directive, which intends to remove outmoded exemptions, such as those for the intra-EU maritime transport sector, and match the taxation of energy products with EU climate goals.
- Promoting innovation and investment in low-carbon technologies and infrastructure, such as renewable energy and carbon capture and storage. This can help accelerate the transition to a low-carbon economy and support the long-term sustainability of ETS.

On April 18th, 2023, the European Parliament endorsed legislative modifications that were proposed on February 8th, 2023, to the EU Emissions Trading Directive. This crucial approval signifies the decision to incorporate the maritime industry into EU's Emissions Trading Scheme and to start implementing in 2024 (European Commission, 2023).

2 OPTIONS WITH DIRECT IMPACT ON GHG EMISSIONS

The objectives of IMO’s Initial Strategy indicate that change is on the way and all parties involved must prepare. To achieve these goals, IMO has proposed a wide range of options at a technical and operational level, some of which will be briefly presented herewith (Valentin, 2022).

2.1 OPERATIONAL MEASURES

Operational measures are a critical component of the IMO's short-term strategies aimed at reducing greenhouse gas emissions from the shipping industry.
The International Maritime Organization has been proactive in facilitating the adoption of these operational measures. Various proposals have been crafted, and a structured framework has been established, which includes the introduction of new regulations aimed at mandating such practices. Additionally, technical guidelines to support the practical application of these measures have been developed. This comprehensive approach ensures that the shipping industry is equipped with the tools and directives needed to make a substantial reduction in GHG emissions.

2.1.1 Voyage optimization

Voyage optimization is a strategy that can be used to reduce carbon dioxide emissions in shipping by improving the efficiency of a vessel's voyage. The goal of voyage optimization is to minimize the energy required to transport cargo from one port to another, by taking into account a range of factors such as weather conditions, ocean currents, and vessel speed. There are several ways that voyage optimization can be achieved:

- **Routing optimization:** Choosing the most efficient route for a vessel based on factors such as the weather, currents, and traffic density. This can help reduce fuel consumption and emissions by minimizing the distance traveled and the time spent in adverse conditions.

- **Speed optimization:** Adjusting the vessel's speed to optimize fuel consumption and emissions, factoring in sea state and current. Slowing down the vessel can significantly reduce fuel consumption and emissions, while still meeting delivery deadlines.
- **Cargo handling optimization:** Optimizing the loading and unloading of cargo to reduce ballast water, which can increase fuel consumption and emissions. Also, optimal trimming is an important factor in a vessel's fuel consumption.
- **Weather routing:** Using real-time weather data to adjust the vessel's route and speed to avoid adverse weather conditions, which can increase fuel consumption and emissions.

By implementing these voyage optimization strategies, shipping companies can reduce fuel consumption, save costs, and reduce their environmental impact by lowering their carbon emissions. Moreover, voyage optimization also enhances safety and helps ensure on-time delivery of cargo.

The International Maritime Organization and other organizations have developed guidelines and tools to help shipping companies implement voyage optimization practices. Digital technology and data analytics play a significant role in these practices. They support real-time monitoring and provide data-driven insights to make informed decisions, helping companies analyze and predict weather patterns, optimize cargo loads, and choose the most efficient route.

Evidence to the above, is a join study conducted by Marubeni Corporation, classification society ClassNK and its software subsidiary NAPA, which gauged the influence of voyage optimisation on a real-world fleet's greenhouse gas emissions and CII ratings (O'Dwyer, 2023). Using NAPA's ship performance model and voyage simulation tools, the study considered data from all trips, weather, and marine conditions in 2021, with a specific emphasis on a group of bulk carriers managed and owned by Marubeni. The research indicated that using software, a ship's fuel consumption and CO_2 emissions could be curtailed by up to 7.3%. Furthermore, it was found that voyage optimisation could boost a ship's CII by an average of 5-6%, thus permitting vessels to preserve their ratings for an additional two to three years (Figure 6).

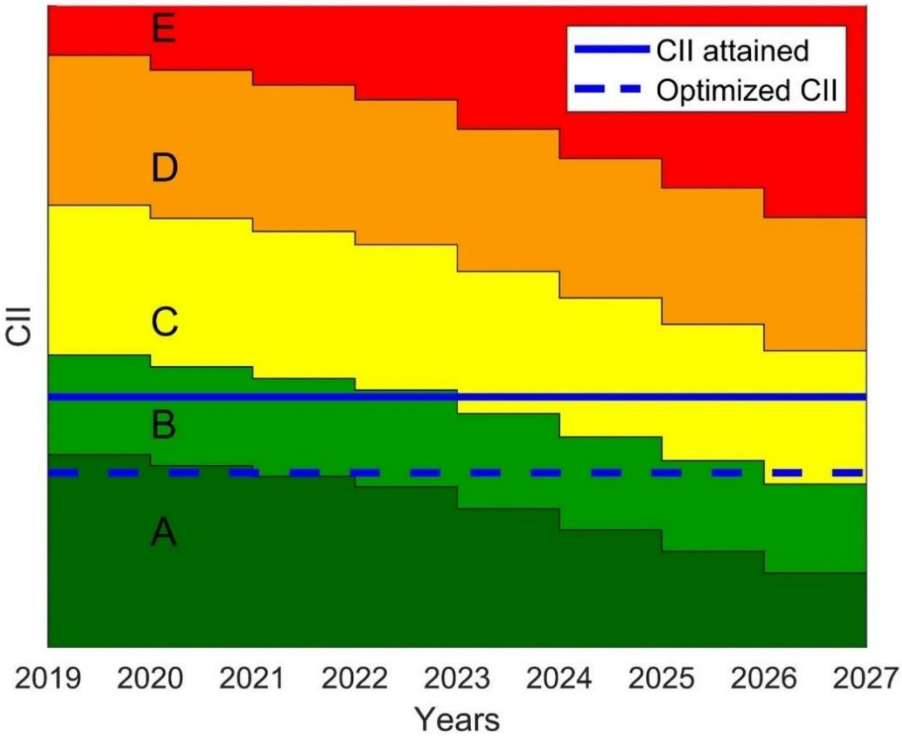

Figure 6

Fuel savings from voyage optimization (O'Dwyer, 2023)

2.1.2 Slow steaming

“Slow steaming” refers to the practice of operating cargo ships at significantly less than their maximum speed to save energy and reduce emissions. This strategy has proven to be effective in reducing the shipping industry's environmental impact and is one of the short-term operational measures that can be used to reduce CO_2 emissions from ships at sea. The benefits of slow steaming depend on the specific ship type, size, and sailing route.

The reduction in emissions from slow steaming is a concept that revolves around the relationship between a ship's speed and the power required for its propulsion. In maritime transportation models, it's commonly assumed that the power needed is proportional to the cube of the ship's speed. Thus, altering the speed will have a nonlinear impact on the power required and, therefore, on fuel consumption and emissions. If the speed is reduced by 10%, the emissions won’t be reduced by 10%, but much more, in this case, 19%. This is because of the cubed relationship: a small decrease in speed leads to a disproportionately large decrease in power demand, fuel consumption, and hence emissions.

While slow steaming is beneficial, further energy savings can be achieved by incorporating additional technical solutions. These might include advanced hull design, propeller optimization, or the use of alternative, cleaner fuels, among others. These technologies can further enhance the energy efficiency of the vessel, adding to the benefits provided by slow steaming.

There are crucial factors to bear in mind when considering the possible downsides of slow steaming. Operating a ship at a speed below its design specifications can change the conditions under which the engine operates, possibly leading to issues like fouling and corrosion due to incomplete combustion and lower operating temperatures. To prevent a substantial rise in exhaust gas temperatures, the activation of blowers may be required when functioning under a lesser load.

Additionally, it's vital to understand that reducing a ship's speed could lead to longer transportation times. This extended duration may necessitate an increase in the fleet size to maintain the same shipping capacity.

Consequently, it's essential to thoroughly analyze both the advantages and disadvantages of slow steaming before adopting it as a strategy to curb CO_2 emissions from maritime vessels.

2.2 TECHNICAL MEASURES

Technical measures encompass modifications to the ships' design and technology with the objective of curbing carbon dioxide emissions. Such strategies typically focus on enhancing the ships' technical facets. They could incorporate initiatives to boost the vessels' energy efficiency, such as upgrading to high-efficiency engines, refining hull design to lessen drag, or integrating technology to recover and reuse waste heat. Further, these technical strategies might include adopting cleaner fuels or technologies like liquefied natural gas, biofuels, fuel cells, or batteries. In this discussion, we will allude to several indicative technological suggestions.

2.2.1 Anti-fouling

Anti-fouling coatings can be considered as a technical measure for reducing CO_2 emissions from ships, as they can help reduce the fuel consumption of ships by improving their hydrodynamic performance. Fouling occurs when marine organisms, such as algae and barnacles, attach to the hull of a ship, creating drag and increasing fuel consumption. By using anti-fouling coatings on the hull, it is possible to prevent or reduce fouling, resulting in smoother and more efficient sailing (IMO, 2023).

Anti-fouling coatings work by releasing biocides or other chemicals that prevent marine organisms from attaching to the hull. The coatings can be applied during the construction of a new ship or as part of regular maintenance for existing ships. The benefits of anti-fouling coatings depend on several factors, including the type of coating used, the sailing route and conditions, as well as the age and condition of the ship.

By reducing fouling and improving the hydrodynamic performance of ships, anti-fouling coatings can help reduce fuel consumption and, in turn, lower CO_2 emissions. IMO has set guidelines for the application of anti-fouling coatings to ensure that they are safe and environmentally friendly.

However, some types of anti-fouling coatings may contain unsafe chemicals that can harm marine life and ecosystems (Yigit Kemal Demirel, 2013). Therefore, it is important to use environmentally friendly coatings and to properly manage and dispose of any waste or byproducts associated with their use (EMSA, 2023). Anti-fouling coatings can be an effective technical measure for reducing CO_2 emissions from ships, but it is important to carefully evaluate their environmental impacts and ensure that they are used in a safe and sustainable manner.

2.2.2 OPS Systems – Cold Ironing

The OPS technology is known by a variety of names: Alternative Maritime Power (AMP), Cold Ironing, Shoreside Electricity and Onshore Power Supply (World Port Sustainability Program, 2023). This technological approach can eradicate the pollutants of supplementary engines at docking, if ships are powered by an environmentally benign energy source, leading in a worldwide emission decrease. Port and ship operators may find the methodology helpful as they consider the advantages of employing cold ironing as an emissions reduction measure (Zis, 2018).

The fact that cold ironing is necessary in Californian ports, compelled terminal and ship operators to make this technological investment. By the end of 2025, all ports in Europe must have a cold ironing facility. The usage of cold ironing as a potential compliance solution in the future may be significantly influenced by other rules that target local emissions, such as Emission Control Zones.

It has been demonstrated that regulation plays a crucial role in the continued uptake of this technology. Illustrative case studies are offered that consider the viewpoints of terminal operators who choose to invest in shorepower facilities, as well as ship operators of various ship types. The findings of the case studies demonstrate that ship operators have an economic incentive to utilize cold ironing in situations with medium and high fuel prices. The cost per tonne of pollutants abated for the port is far less than the existing estimates of the external costs of emissions.

Consequently, if regulatory bodies support the further implementation of this technology by ship operators and ports, shore power may be a feasible solution for the marine industry to reduce emissions.

2.2.3 Onboard Carbon Capture

Onboard Carbon Capture (OCC) for shipping is a proposed solution to reduce greenhouse gas emissions directly from vessels (Mærsk Mc-Kinney Møller Center, 2022). It's an application of the Carbon Capture and Storage (CCS) concept, specifically designed for the maritime industry (National Grid, 2023). Here's how it would work in principle:

1. **Capture:** This stage involves capturing or separating CO_2 from the ship's exhaust gases. Various technologies can be used for this process, including absorption, adsorption, membrane or cryogenic separation. The captured CO_2 is then prepared for transport, often by compressing it into a liquid form to reduce its volume.
2. **Onboard Storage:** Since the CO_2 is captured directly on the ship, it needs to be stored onboard until the ship reaches a port where it can be offloaded. This presents a unique challenge for ships, as space is typically at a premium. The storage system must be compact and safe, and it must also prevent the CO_2 from escaping.

3. **Offloading and Transport:** When the ship reaches a port, the captured CO_2 would be offloaded and transported to a storage site. This could be done through pipelines or special CO_2 transport ships.
4. **Permanent Storage:** Finally, the CO_2 is securely stored to prevent it from being released into the atmosphere. This could be in depleted oil and gas fields, deep saline aquifers, or other suitable geological formations.

While the concept of OCC is promising, it is still under development and there are significant technical and economic challenges to be overcome. The power needed to run capture and compression equipment could be significant, which would increase the ship's fuel consumption and offset some of the emission reductions. Moreover, developing a global infrastructure for offloading, transporting and storing CO_2 would be a massive undertaking. As such, while OCC could be a part of the solution for reducing maritime emissions, it would likely need to be used in combination with other strategies, such as improved energy efficiency and alternative fuels (Mærsk Mc-Kinney Møller Center, 2022).

Onboard carbon capture is being evaluated as a potential technology to help reduce carbon emissions in the maritime sector, alongside energy efficiency measures and alternative fuels. OCC has the capability to work with all forms of carbon-based fuels, be they fossil, electrochemical, or biofuels, thus positioning it as a promising medium- to long-term solution for shipping decarbonization.

Nevertheless, the success of OCC hinges on various factors, such as technological advancements in OCC, its commercial feasibility, the price and availability of alternative fuels, and future emissions-related regulatory demands. While OCC can significantly lower emissions, current studies indicate that its CO_2 mitigation costs are substantial. Despite this, with continued progress, OCC could serve as a medium-term solution to decrease the emission intensity of existing vessels powered by fossil fuels.

2.2.4 Alternative fuels

A critical area of focus in decarbonizing the shipping sector is the transition from conventional fossil fuels to alternative fuels. These alternative fuels represent a diverse range of energy sources, from biofuels and hydrogen to Liquefied Natural Gas (LNG) and ammonia, each with its own unique benefits and challenges. The adoption of alternative fuels in shipping offers the potential to drastically reduce greenhouse gas emissions, improve air quality, and align the industry with international climate goals.

However, widespread implementation requires overcoming significant hurdles, such as infrastructure development, technological advancement, and regulatory compliance. Despite these challenges, the shift towards alternative fuels is a necessary and promising step towards a sustainable future in maritime transport.

2.2.4.1 Biofuels

Biofuels are a promising option for decarbonizing the maritime sector. Biofuels are produced from renewable sources such as agricultural crops, forestry residues, and waste materials, and can be used as a substitute for fossil fuels in ship engines without requiring significant modifications (Marine Offshore Bureau Veritas, 2023).

There are several types of biofuels that can be used in the maritime sector, including biodiesel, biogas, and bioethanol. Biodiesel is a renewable fuel that can be produced from vegetable oils, animal fats, or used cooking oil, and can be used as a direct substitute for diesel fuel. Biogas is produced from organic waste materials, such as sewage, agricultural waste, and landfill gas, and can be used as a fuel for ship engines. Bioethanol is produced from agricultural crops, such as sugarcane and corn, and can be used as a fuel for ships. For its part, the Mediterranean Shipping Company (MSC) has successfully tested biofuel blends with the goal of initially decreasing greenhouse gas emissions by 15-20%, then gradually increasing to the entire possible reduction of 80-90%.

Biomass-derived fuels are also being researched to reduce CO_2 and sulphur emissions by up to 90%.

According to some studies, the use of biofuels in shipping can reduce greenhouse gas emissions by up to 90% compared to conventional fossil fuels. On the other hand, today's global shipping firms are turning to “traditional” solutions given by Mother Nature, such as wind power turbines, to reduce CO_2 emissions by up to 90%.

However, there are also some challenges associated with the use of biofuels in shipping, as rivalry with the food production business may be a hurdle. The production of biofuels requires significant amounts of land and water resources, and there are concerns about the potential competition for resources between biofuel production and food production. In addition, the availability and cost of biofuels can vary depending on local conditions and the availability of feedstock.

2.2.4.2 Hydrogen

Hydrogen fuels are emerging as a promising alternative to traditional fossil fuels in the shipping industry, with the potential to significantly reduce emissions and help the sector move towards a more sustainable future.

Hydrogen, when used as a fuel, produces water as the only byproduct, making it a zero-emission fuel source at the point of use. When hydrogen is produced from renewable energy sources, such as solar or wind power, the entire supply chain can be virtually carbon-free. This “green” hydrogen could play a critical role in decarbonizing the shipping industry and contribute substantially to global emission reduction goals (DNV, 2021).

However, the shift to hydrogen fuel also comes with its own set of challenges. Currently, the production of green hydrogen is expensive and less energy-efficient compared to fossil fuels. Additionally, storing hydrogen is technically challenging due to its low energy density, requiring either high pressures or low temperatures. Also, the considerable physical space required to store the hydrogen for long voyages, could compromise the vessel's cargo capacity (ABS, 2021).

Moreover, the infrastructure for hydrogen fuel – from production facilities to refueling stations – is still underdeveloped and would require substantial investment to scale up. There are also safety considerations associated with the use of hydrogen as a fuel due to its flammability and the fact that it's odorless, colorless, and less dense than air, making leaks harder to detect.

Finally, the utilization of hydrogen as a fuel necessitates a comprehensive retrofitting of existing engines, which entails a significant financial investment.

Despite these challenges, numerous pilot projects and research initiatives are underway to improve the production, storage, and distribution of hydrogen. If these technical and economic obstacles can be overcome, hydrogen has the potential to significantly reduce the carbon footprint of the shipping industry.

2.2.4.3 Ammonia

Ammonia, like hydrogen, is gaining attention as a potential alternative fuel in the shipping industry, primarily because of its potential to help reduce greenhouse gas emissions.

When used as a fuel, ammonia does not emit carbon dioxide during combustion, making it a carbon-neutral fuel choice in operation. Furthermore, when ammonia is manufactured from renewable resources using green hydrogen and air, which is primarily nitrogen, it can be considered a “green” fuel, thus providing a pathway for the shipping industry to decarbonize.

Ammonia has a few key advantages over hydrogen that make it an attractive option. Firstly, it's easier to store and transport, compared to hydrogen, due to its higher energy density and the fact that it remains a liquid at much higher temperatures. Secondly, the global infrastructure for ammonia is considerably more developed than for hydrogen, due to its main use as a fertilizer.

Still, there are challenges that need to be addressed before ammonia can be widely adopted as a marine fuel. Currently, most ammonia is produced using natural gas or coal, both of which are carbon-intensive processes. To truly realize ammonia's potential for emission reductions, the production process needs to shift towards using green hydrogen.

Furthermore, ammonia is highly toxic and handling it requires careful safety measures. It also has a lower energy content compared to traditional marine fuels and burns poorly at ambient conditions, which means that engines and fuel systems would need to be redesigned or adjusted to use it effectively (NABU, 2023).

Nevertheless, progress is being made. Various initiatives are underway to develop engines and fuel systems that can use ammonia, as well as to improve the production of green ammonia. Should these challenges be successfully managed, ammonia has the potential to play a significant role in reducing the shipping industry's carbon footprint.

3 MARKET-BASED MEASURES

Market-based measures (MBMs) are mechanisms that have been introduced to enhance global ambitions for reducing greenhouse gas emissions from the shipping industry. They use economic incentives to promote the reduction of greenhouse gas emissions, while effectively making industry bear the cost of the pollution it causes. The principle is to associate a cost with emissions, thus encouraging those who emit greenhouse gases to adopt cleaner and more efficient technologies and practices. In the context of shipping, these can significantly accelerate the adoption of technical and operational measures in several ways:

- **Cost-Effective Decarbonization:** By putting a price on carbon emissions, like in carbon taxes or cap-and-trade systems, these measures make it financially more attractive for shipping companies to invest in cleaner technologies and fuels. The higher the cost of emitting CO_2, the more economical low-carbon alternatives become.
- **Investment Stimulation:** The prospect of a future carbon price can stimulate investment in the research and development of new technologies and fuels, helping to accelerate their market readiness and commercial availability.
- **Operational Efficiency:** MBMs can make it more cost-effective to adopt operational measures that reduce fuel consumption and emissions, like slow steaming, optimized voyage planning, or improved maintenance.
- **Revenue Recycling:** The revenues generated by some MBMs, like a levy or a cap-and-trade system, can be used to fund additional measures to reduce emissions, such as research and development, infrastructure for new fuels, or subsidies for retrofitting existing ships.
- **Fuel Switching:** By making traditional bunker fuels more expensive due to their carbon content, MBMs can accelerate the shift towards low-carbon or zero-carbon fuels.
- **Behavioral Change:** MBMs incentivize behavioral change in the entire supply chain, not just among ship operators but also among cargo owners, charterers, and others, creating a comprehensive system favoring low-carbon operations.

Market-based measures create an economic environment where it makes financial sense to invest in lower-carbon technologies and practices, thereby accelerating the decarbonization of shipping. However, they need to be well-designed to ensure they are effective, fair, and do not lead to unintended consequences.

3.1 PROPOSALS OVER THE YEARS

So far, a range of MBMs have been put forward by both governments and observer organizations. These proposals encompass everything from contribution systems for CO_2 emissions from international shipping with the creation of a specific fund, to emission trading programs and even plans that evaluate a ship's efficiency through both its design and operational aspects. There are several MBMs that have been proposed:

- **International GHG Fund for Ship Emissions** *(Cyprus, Denmark, the Marshall Islands, Nigeria, and IPTA (MEPC 60/4/8)):* Sets a global reduction target for international shipping, which can be set by UNFCCC or IMO. Emissions above the target line would be partially offset by the purchase of approved emission reduction credits. Ships would contribute to the offsetting activities for each tonne of bunker fuel purchased.
- **Leveraged Incentive System (LIS)** *(Japan (MEPC 60/4/37)):* Contributions to the GHG Fund are collected on marine bunker. Part thereof is repaid to ships reaching or exceeding set efficiency goals and designated as “excellent performance ships” (IMO, Market-Based Measures, 2021).
- **Jamaica** *(MEPC 60/4/40):* A standard emissions fee is levied on all vessels stopping at their separate ports depending on the quantity of fuel spent by the particular vessel on its route to that port (not bunker suppliers).
- **Ship Efficiency and Credit Trading (SECT)** *(United States (MEPC 60/4/12)):* Sets obligatory energy efficiency criteria for all ships. An efficiency-credit trading scheme would be formed as one method of meeting the criterion. Throughout time, these criteria would become increasingly strict.
- **Vessel Efficiency System (VES)** *(World Shipping Council (MEPC 60/4/39)):* This system establishes mandated efficiency criteria for new and existing ships. Each vessel would be evaluated in relation to the need to enhance its efficiency by X% below the average efficiency (baseline) for the given vessel class and size. With time, the standards will become more stringent. Existing ships that do not meet the requisite standard through technological upgrades will be charged a price for each tonne of fuel spent.
- **International Shipping Emission Trading System (ETS)** *(Norway (MEPC 61/4/22)):* Creates a sector-wide cap on international shipping net emissions. Each year, a number

of permits (Ship Emission Units) matching to the cap would be auctioned off on the market. After that, the units may be exchanged.

- **Global Emissions Trading System (ETS) for International Shipping** *(United Kingdom (MEPC 60/4/26)):* Differs from the Norwegian ETS plan in two ways; the mechanism of awarding emissions permits (national auctioning rather than global auctioning) and the technique for determining the emissions ceiling (set with a long term declining trajectory).
- **Emissions Trading System (ETS) for International Shipping** *(France (MEPC 60/4/41)):* Provides more information on auction design in the context of a shipping ETS. In every other way, the plan is identical to the Norwegian ETS proposal (IMO, Market-Based Measures, 2021).
- **Market-based Instruments: A Trade and Development Penalty** (*Bahamas (MEPC 60/4/10)):* Demands that any fees imposed be appropriate to the impact of international shipping on global CO_2 emissions.
- **Rebate Mechanism (RM) for a Market-based international shipping instrument** *(IUCN (MEPC 60/4/55)):* Compensation for the financial effect of an MBM should be provided to poor nations. It might be used for any revenue-generating marine MBM.

MEPC 60 requested that an expert panel do a feasibility study and effect assessment on previously suggested MBMs by states and observer groups. The expert group's findings were presented at MEPC 61, where there was a lengthy discussion about how to move forward with the development of acceptable MBMs. The Committee resolved to host an Intersessional Meeting of the Working Group on GHG Emissions from Ships (GHG-WG 3) in March/April 2011, the results of which were reported to MEPC 62. Nevertheless, owing to time restrictions and the hectic program of MEPC 62, it was decided that MBMs would be considered during the next MEPC session (MEPC 63 in February/March 2012).

MEPC 63 continued its discussion of proposed MBMs and agreed on the need to conduct an impact assessment of the MBM proposals, with a focus on potential impacts on consumers and industries in developing countries in general, and, in particular, least developed countries, small island developing states, and remotely located developing countries with long trading distances, and discussed in detail the methodology and criteria that should be used.

MEPC 65 resolved to postpone talks on MBMs and associated concerns until a future session after receiving various comments on the subject (IMO, Market-Based Measures, 2021). The halting of the dialogue on MBMs in 2013 likely reflected a political process and the widely differing opinions among IMO member states regarding greenhouse gas emissions.

MEPC 80, adopted an enhanced IMO GHG Strategy. This updated strategy is set to establish more aggressive greenhouse gas reduction goals for the shipping industry and to provide clear-cut reduction targets for greenhouse gas emissions in the sector. The laid out broad plan of technical and economic strategies, all aim at guiding the global shipping industry towards the complete elimination of GHG emissions by 2050.

3.2 INFLUENTIAL PARAMETERS AND CHALLENGES

While market-based measures have been progressively gaining traction as a mechanism to curb carbon emissions, they are not without their own distinct set of challenges and difficulties. These obstacles, which range from technical intricacies to economic implications, require careful consideration and proactive management to ensure the long-term success and sustainability of these initiatives. Among the various industries, the maritime sector faces unique hurdles in implementing these measures.

To start with, the effectiveness of carbon trading relies heavily on accurately tracking and reporting carbon emissions. This principle is crucial in the shipping sector, where tracking emissions can be complex. In the next chapter, a more in-depth description of the systems currently used to monitor, report, and verify shipping emissions is provided. These systems play a key role in ensuring we have reliable data about carbon emissions, which is fundamental for carbon trading to work effectively.

Furthermore, implementing market-based measures in the shipping industry isn't a straightforward task. It comes with added administrative responsibilities that can be complex. These include the need to accurately monitor emissions, comprehend intricate rules and regulations, and manage the technicalities of trading systems. Small to medium-sized enterprises may find this particularly difficult due to limited resources and expertise. This complexity, therefore, raises issues of fairness, as the ability to comply effectively with these measures can vary greatly based on the size and resource capacity of different companies. This complexity of MBMs does not only create an administrative burden for companies, but also for national administrations (Psaraftis H. , 2012). Legal aspects of implementing and enforcing MBMs can be daunting and resource-intensive for these administrations. The spectrum of tasks includes developing and maintaining regulatory frameworks, monitoring compliance, and enforcing penalties for non-compliance.

Market-based measures inevitably bring about an escalation in costs for shipping companies. These additional costs, encompassing increased fuel expenditures, heightened maintenance costs and potential capital expenses associated with ship modifications, are all integral elements of ship running costs, one of the key determinants of maritime transport costs (Isabelle Rojon, 2021). The introduction of a maritime carbon pricing system, a market-based measure, is anticipated to escalate freight costs by 0.4% to 16%. This prospect raises concerns, especially for Small Island Developing States (SIDS) and Least Developed Countries (LDCs) due to the existing high transport costs (Psaraftis H. Z., 2021). These countries already face geographic and economic challenges which elevate their transport costs, and such a carbon pricing system could exacerbate these difficulties. Hence, the adoption of MBMs could potentially increase global trade participation disparities.

On the other hand, carrying out market-based strategies in the shipping industry often faces political obstacles. These measures can spark political debates and meet resistance, making global adoption challenging. The disagreements can stem from differing national interests, resource availability, and environmental priorities. Such political disputes may compromise the effectiveness of MBMs, potentially leading to weaker policy design, implementation delays, or inadequate enforcement. Therefore, achieving consensus, promoting international cooperation, and navigating geopolitical complexities are crucial.

Last but not least, the introduction of carbon pricing in the shipping industry may lead to intensified competitive pressures, a development that could particularly impact smaller operators. These companies, which typically own less efficient, older vessels and have limited accessibility to carbon credit trading markets, may face discrimination under carbon pricing regimes (ITF, 2022).

Such a policy might inadvertently tilt the market balance in favor of larger carriers, which generally possess the financial means to modernize their fleets to meet new regulatory requirements. This financial capability of larger companies could further accelerate the already progressing trend of market consolidation, potentially leaving smaller companies struggling to compete.

The gap becomes even more significant in periods of depressed freight rates, during which the benefits of operating larger, more energy-efficient vessels are highlighted. Under these circumstances, smaller operators could find themselves under greater pressure and risk being forced out of the market.

Carbon pricing could potentially result in a dual-tiered shipping market. This division could see the more energy-efficient ships largely servicing international routes, while their less efficient counterparts might be confined to regional or domestic routes, or secondary markets likely in developing or emerging economies. This potential split in the market might not only enhance economic inequalities, but also create an uneven playing field in the global shipping industry.

3.2.1 Data collection and verification

The first action in the journey to carbon pricing in the shipping industry is to ensure that GHG emissions from ships are accurately monitored and that the data collected is validated. Only with a robust tracking system in place can an effective carbon pricing mechanism be designed and implemented.

The European Union has implemented its own system for Monitoring, Reporting, and Verifying (MRV) CO_2 emissions from large ships using EU ports. Introduced in 2015 and effective in 2018, the EU MRV Regulation (Regulation 2015/757) is an essential part of the EU's strategy to reduce greenhouse gas emissions from maritime transport. Under the MRV system:

- **Monitoring:** Ships with over 5,000 GT (regardless of their flag) are required to monitor and annually report their CO_2 emissions, fuel consumption, and other relevant information when they are traveling to, from, and between EU ports. The monitoring plans need to be submitted to verifiers for assessment.
- **Reporting:** The shipping companies are required to prepare an emissions report for each ship under their responsibility on an annual basis. The data must be verified by an independent verifier before the report is submitted to the European Commission and the flag state.

- **Verification:** The role of the verifier is to check the emissions report and the data contained therein. If everything is in order, the verifier issues a Document of Compliance (DoC) to the ship. Ships that have not surrendered a valid DoC may be subject to penalties.

The EU MRV aims to promote transparency and stimulate competition among shipping companies to reduce emissions. As the EU is planning to include shipping in its Emission Trading System, the MRV is considered a first step towards that end. The data collected and verified through the MRV system will be used to determine a ship's obligation under the ETS.

On the other hand, following the EU's strategy, IMO introduced the International Maritime Organization's Data Collection System (IMO DCS) as a global initiative; a system designed to gather and analyze data related to the energy efficiency of ships. It became mandatory for all ships of 5,000GT and above under a regulation that came into force on March 1st, 2018 (IMO , 2019). Starting from 2019, IMO requires the mentioned ships to collect data on their fuel oil consumption. The system aims to gather detailed and accurate data on fuel consumption, as well as other relevant data such as the distance traveled and hours underway, which can then be used to calculate the energy efficiency of each ship.

This data is collected on a per-voyage basis and reported to the flag state of each ship at the end of each calendar year. The flag state, or a recognized organization acting on its behalf, then verifies the data to ensure accuracy before sending it to IMO, which maintains a central database, the IMO Ship Fuel Oil Consumption Database. This not only helps IMO understand fuel consumption patterns and the energy efficiency of the global fleet but also informs decisions regarding further measures for improving energy efficiency and reducing GHG emissions.

The EU MRV and IMO DCS are key regulations aimed at monitoring and verifying the reported greenhouse gas emissions data from ships. These regulations play a critical role in the strategies of both the IMO and the EU, as they help paint a comprehensive picture of the environmental impact of maritime operations. They serve as an accountability mechanism, enabling the IMO and the EU to implement economic measures to incentivize reductions in GHG emissions from ships.

3.2.2 Carbon Leakage

Carbon pricing mechanisms can potentially give rise to an issue known as carbon leakage, particularly when these mechanisms are not globally applied, but instead are limited to specific regions (ITF, 2022). In the context of the shipping industry, companies might exploit loopholes in regional carbon pricing structures to evade their responsibilities. For instance, shipping firms could manipulate the system by altering their vessels' flags, assuming the carbon pricing is tied to a country's flag. Alternatively, they could strategically change their ports of call or shipping routes, if the carbon pricing is applicable to specific ports or territorial waters (Figure 7). Such actions could undermine the effectiveness of regional carbon pricing schemes.

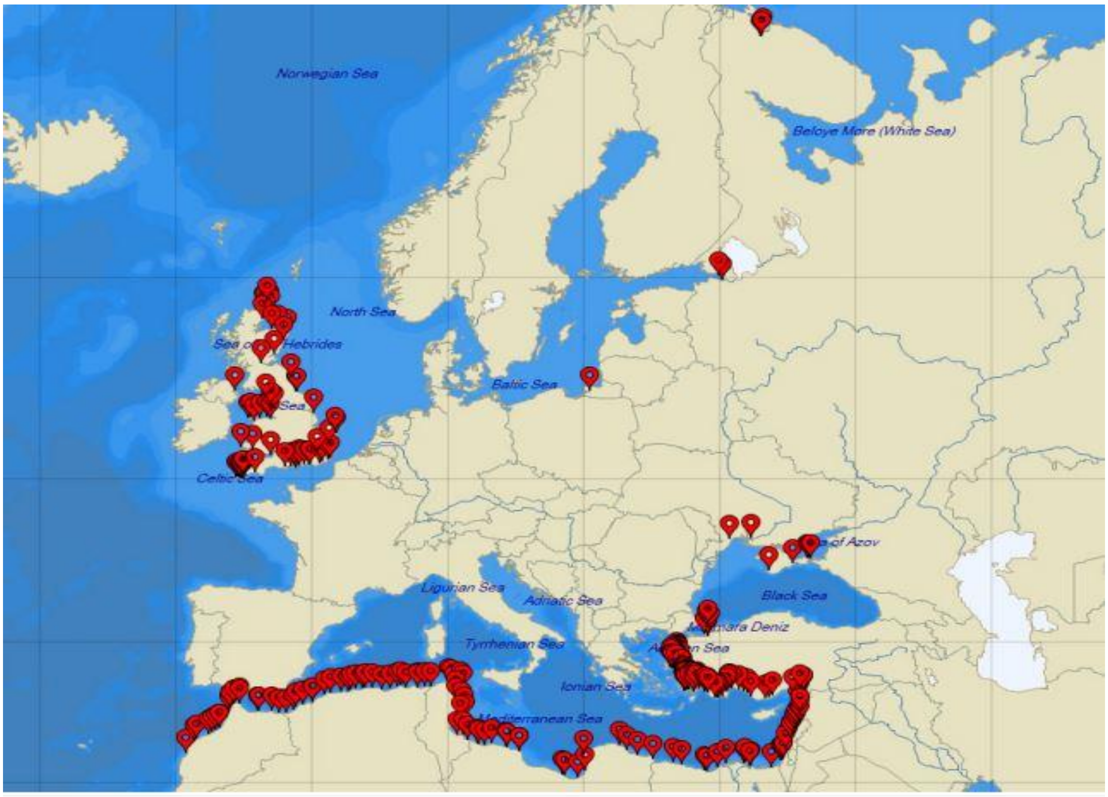

Figure 7

Map showing ports within 300 nautical miles from EU Member State borders (Holman Fenwick Willan LLP, 2022)

The majority of research on carbon leakage within the shipping industry is concentrated on the potential implications of incorporating the shipping sector into the EU's ETS. Yet, this scheme is not limited to emissions from shipping between EU ports only. The proposed scope, extends beyond the region's borders, as it includes 50% of the emissions from voyages originating from a non-EU port and destined for an EU port, and vice versa. This widened scope is part of the EU's strategic effort to mitigate the risk of carbon leakage, ensuring comprehensive management of carbon emissions from the shipping industry, regardless of where the voyage begins or ends.

Furthermore, a fundamental tool in the EU's plan to tackle the possible risk of carbon leakage is the Carbon Border Adjustment Mechanism (CBAM), which will enter into force in 2024. This arrangement necessitates that importers of particular carbon-intensive goods to the EU pay a fee that matches the charge imposed on comparable industries within the EU under the ETS. Essentially, this mechanism extends the carbon pricing burden borne by EU firms to overseas producers of similar goods. The risk of carbon leakage could become reality if the greenhouse gas emissions, regulated under the EU ETS, were counterbalanced by entities involved in these industries, moving their operations to areas beyond the ETS jurisdiction. The risk also exists if EU businesses were to increase their imports from such non-regulated areas. Therefore, the CBAM will function as a safeguard, ensuring that the carbon reduction efforts made within the EU under the ETS are not compromised by activities occurring outside its regulatory framework (EU Taxation and Customs Union, 2023).

3.2.3 Misaligned incentives between stakeholders

Implementing market-based measures in shipping for decarbonization often involves a broad range of stakeholders, including ship owners, operators, charterers, shippers, port authorities, and regulators. The incentives and impacts of MBMs can differ significantly among these stakeholders, leading to potential “split incentives” or “misaligned incentives”. Ship owners and operators are directly responsible for implementing MBMs, as they are typically the ones who decide on investment in new technologies or operational practices to reduce emissions. Despite that, they might not have sufficient financial incentive to do so if the costs cannot be passed on to charterers or shippers.

Then again, charterers hire ships from the owners, and shippers pay to transport goods. They benefit from reduced fuel costs (and potentially reduced freight rates) if the ships they use are more energy efficient. Even so, they may not have direct control over the ships' design or operation and may not be willing to pay higher rates to use more environmentally friendly ships.

The shipping industry often exhibits seemingly irrational operating patterns. Vessels are often seen sailing at high speeds, only to end up waiting upon arrival at the port. This “sail fast, then wait” (SFTW) practice leads to needless fuel consumption and additional emissions. Although these actions make economic sense to some parties, from an emissions perspective, the shipping industry must strive for better practices.

Complexities abound in reducing emissions in the ocean supply chain, due to the wide range of decision-making drivers, depending on one's position in the value chain. The overall efficiency of the process, especially concerning fuel efficiency per transport work, is suboptimal. Studies estimate that through alterations in process and speed profile alone, 15-20% of emissions could be theoretically eliminated without negatively impacting fleet capacity. This alone could help the industry achieve half the IMO 2030 GHG target. With stricter requirements likely in the future, tackling these inefficiencies quickly is crucial (BIMCO, 2023).

The issues of inefficiency don't stem from poor decision-making but are often due to a siloed value chain where professionals are focused on improving their operations for profitability. To reduce GHG emissions, the industry needs to reconsider its established processes and incentives, which often promote inefficiency.

Voyage Charter Parties, which have a significant impact on emissions, often motivate vessel owners to sail at high speeds, even if the port berth isn't available, to maximize demurrage charges. However, this contributes to excessive fuel consumption and emissions, negatively affecting the vessel's Carbon Intensity Indicator rating. To counter this, the industry needs to re-examine the Charter Party legal framework to encourage not only maximized revenue but also minimized emissions.

While owners might seek to maximize demurrage charges by reaching the port as soon as possible, the environmental implications of this practice are a concern. Advanced technology offers opportunities for better collaboration between Charterers and Owners to address these issues and comply with new GHG regulations more effectively.

Moreover, many public terminals and ports continue to operate on a first-come, first-served basis, leading to a race to the queue and fuel waste. To meet decarbonization targets, ports need to adopt alternative approaches, leveraging new technologies.

Time Charter Parties (TCPs) can also result in sub-optimal speeds due to split incentives, with Owners having little incentive to invest in fuel efficiency. The introduction of CII regulations is altering these motivations, necessitating a more collaborative relationship between Owners and Charterers.

The industry should aim to move away from a claims-based approach and use third-party modeling and connectivity to collaboratively drive improvements. Redefining key Charter Party clauses could help resolve many of the systemic inefficiencies within the industry, leading to a win-win situation for all stakeholders, including the environment.

Key changes needed to reduce emissions include aligning incentives between Owners and Time Charterers, rewarding Owners financially for improving vessels under Time Charter Party terms, incentivizing maintenance of a specified CII grade under TCP terms, moving away from single warranted speeds and implementing new Voyage Charter Party terms to facilitate schemes like Virtual Arrivals and Just-in-time Arrivals (BIMCO, 2023).

Implementing market-based measures, such as an emissions trading scheme or carbon tax, can significantly influence the behaviors and decisions of both ship owners and charterers in the maritime industry. By pricing carbon emissions, an MBM not only incentivizes reduced emissions, but also encourages energy efficiency and cooperation between different stakeholders.

The cost of ETS or carbon tax compliance is directly linked to fuel consumption. Logically, the party responsible for fuel costs – the operator - should also cover the cost of ETS compliance. This arrangement aligns with the principle of attributing costs to the parties who have the most influence over fuel consumption and hence emissions (GARD, 2022).

Ship owners, particularly under voyage charter parties, have several incentives to enhance efficiency and reduce emissions. High fuel costs and ETS compliance costs can motivate actions such as slow steaming, which reduces fuel consumption but increases voyage duration. They might also incentivize investment in energy-efficient technologies, as the cost savings from reduced fuel consumption can offset the initial investment over time.

Charterers, on the other hand, are incentivized to adopt greener operational practices and charter more energy-efficient vessels to mitigate the high costs of fuel and carbon allowances. This could involve actions like voyage optimization, slow steaming, or specifically selecting vessels with better fuel efficiency.

Finally, incorporating fuel efficiency or emission reduction clauses into charter party agreements can formalize the sharing of responsibilities and costs between ship owners and charterers. These agreements could establish standards for energy efficiency or emissions reductions or arrange for charterers to contribute to the costs of energy efficiency improvements.

Through carbon pricing, this problem can be addressed, and the interests of ship owners and charterers can be better aligned. This approach can create a more level playing field and promote the broader adoption of energy-efficient operational practices and technologies in the maritime sector.

3.3 MARGINAL ABATEMENT COST CURVES

Marginal Abatement Cost Curves (MACC) are graphical representations that display the relationship between the cost of reducing one additional unit of pollution (in this case, emissions from shipping) and the total amount of pollution reduction achieved. The curve shows the cost-effectiveness of different abatement measures, enabling policymakers and industry stakeholders to identify the most efficient ways to reduce emissions.

In relation to market-based measures for shipping, MAC curves play a crucial role in designing and implementing effective policies. The financial cost and benefit of specific acts' abatement are measured and compared using MACCs. They utilize the unit $/t$CO_2$eq, which stands for dollars per tonne of carbon dioxide equivalent.

This is the connection between MAC curves and the Emission Trading System for the shipping industry:

- **Identifying cost-effective measures:** MAC curves provide insight into various abatement measures that can be adopted by the shipping industry. The curve displays the least expensive measures first, helping policymakers and industry stakeholders prioritize strategies that offer the most significant emissions reduction at the lowest cost.
- **Setting the cap:** Policymakers can use MAC curves to estimate the optimal cap for emissions. By analyzing the curve, they can identify the level of emissions reduction

that balances the environmental benefits with the associated costs. This helps in setting an appropriate cap for ETS that incentivizes companies to invest in abatement technologies and practices.

- **Allocating allowances:** MAC curves can be used to determine the initial allocation of emission allowances among shipping companies. By analyzing the curve, policymakers can allocate allowances proportional to the abatement potential and cost of each company, ensuring a fair distribution and promoting cost-effective emissions reduction.
- **Price discovery:** When shipping companies engage in the trading of emission allowances, MAC curves serve as vital tools for determining the price. The market price for these allowances will ultimately align with the marginal abatement cost, mirroring the expense associated with reducing the last pollution unit to achieve the emissions cap. This pricing mechanism encourages shipping companies to prioritize investment in abatement measures that provide the most cost-efficient means of reducing their emissions (Psaraftis H. , 2012).
- **Dynamic adjustments:** MAC curves can change over time as technologies improve and more information becomes available. Policymakers can use updated curves to make adjustments to ETS, such as modifying the cap or reallocating allowances, ensuring the scheme remains effective in driving emissions reduction (IMO, 2020).

Marginal Abatement Cost Curves serve as a valuable tool used to evaluate and prioritize the most cost-effective options for reducing GHG emissions. They guide the decision-making process of both policymakers and industry stakeholders. In addition, they help identify which emission reduction measures could be the most cost-effective, provide a foundation for setting and distributing emission caps, and aid in establishing the carbon price within a market mechanism.

The *Fourth Greenhouse Gas Study* conducted by IMO in 2020 presents a revised Marginal Abatement Cost Curve for the shipping industry. In the context of this study, the MACC is developed considering several potential means to enhance energy efficiency or decrease the carbon intensity of the shipping industry. These means include:

- **Energy-saving technologies:** Implementing advanced technologies that can help ships use energy more efficiently, thus reducing the amount of fuel consumed and the associated CO_2 emissions.

- **Use of renewable energy:** Harnessing renewable energy sources, such as wind or solar power, to supplement or replace traditional fuel sources on ships.
- **Use of alternative fuels:** Switching to fuels with a lower carbon content than conventional marine fuels, such as biofuels or hydrogen.
- **Speed reduction:** Slowing down ships to reduce fuel consumption and emissions. This is because fuel consumption – and thus CO_2 emissions – tends to increase exponentially with speed.

The updated MACC, illustrated in Figure 8, considers all the planned modifications to the Energy Efficiency Design Index regulations, a performance-based mechanism that aims to encourage continuous technical development of all the components influencing the energy efficiency of a ship. However, the MACC does not factor in the impact of the Energy Efficiency Existing Ship Index, a measure designed to enhance the energy efficiency of existing ships.

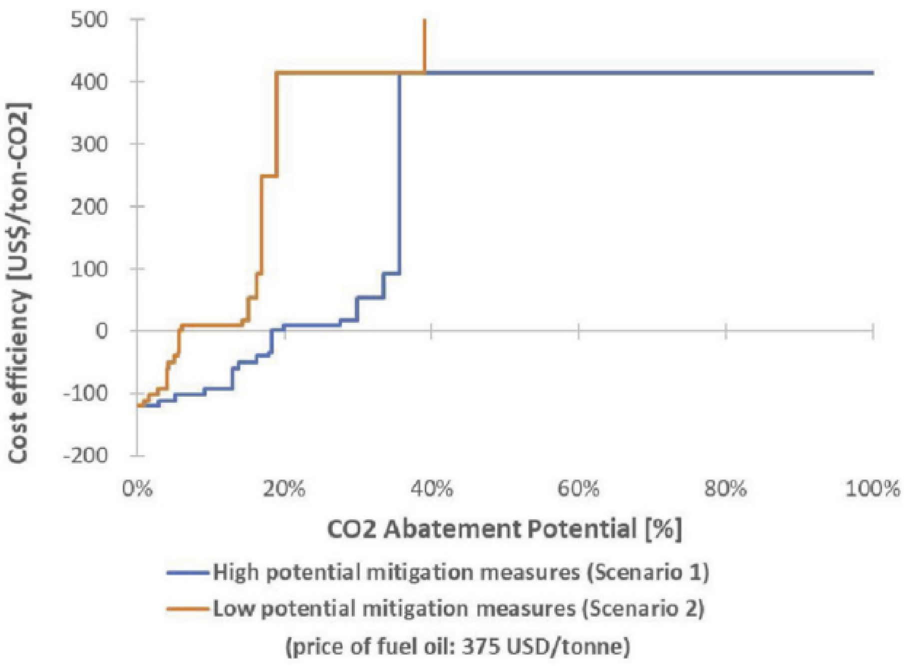

Figure 8

Marginal abatement cost curve for 2050. Source: (IMO, Fourth GHG Study, 2020)

The study, based on certain assumptions, mainly regarding the future costs of zero-carbon fuels, concludes that the targets established in the IMO Initial Strategy are attainable.

According to MACC, the use of alternative fuels could account for roughly 64% of the total CO_2 reduction, demonstrating a significant potential contribution to achieving the shipping industry's decarbonization goals (Cullinane & Yang, 2022).

A negative Marginal Abatement Cost implies that the ship owner would financially benefit from implementing the corresponding measure. In other words, this action would not only boost the owner's profits, but also decrease CO_2 emissions. It's a win-win situation that doesn't require regulation to enforce the measure. Put another way, even if a market-based measure, that doesn't actively push for emission cuts, is introduced, there could still be a decrease in CO_2 emissions. This is because measures that have a negative Marginal Abatement Cost – meaning they are financially beneficial to implement – would probably be adopted due to their cost savings and profit potential.

On the flip side, if a MAC is positive, the ship owner wouldn't be motivated to put the measure into practice on their own, because it wouldn't bring financial gains. In such a case, a regulation or law would need to be put in place to ensure that the measure is carried out.

The projected price of fuel plays a critical role in shaping MAC curves. When the price of fuel is high, it becomes more economically viable to adopt measures that reduce emissions, as the cost of continuing with the status quo becomes increasingly burdensome (Psaraftis H. , 2012). In this context, MAC curves show a steeper decline, indicating that emission reduction measures offer more significant cost savings compared to high fuel costs. Conversely, when the projected price of fuel is low, MAC curves tend to flatten out. This means that the cost savings associated with implementing emission reduction strategies may not be as substantial.

As indicated in Psaraftis, *Market-based measures for greenhouse gas emissions from ships: a review*, a MAC curve proves to be highly valuable when assessing the impact of a bunker levy on CO_2 emissions (Psaraftis H. , 2012). In Figure 9 presented below, two MAC curves are displayed: the upper one represents the situation prior to the application of the levy, while the lower one represents the scenario after the levy is applied. Upon imposing the levy, the fuel price rises to PFUEL + LEVY. Assuming that LEVY is a positive value and that the levy itself does not result in fuel price fluctuations, the MAC curve experiences a uniform decline of LEVY/F. This indicates that by assuming the equilibrium point of CO_2 emissions lies where MAC equals zero, we can readily determine the reduction in CO_2 emissions, denoted as ΔCO_2.

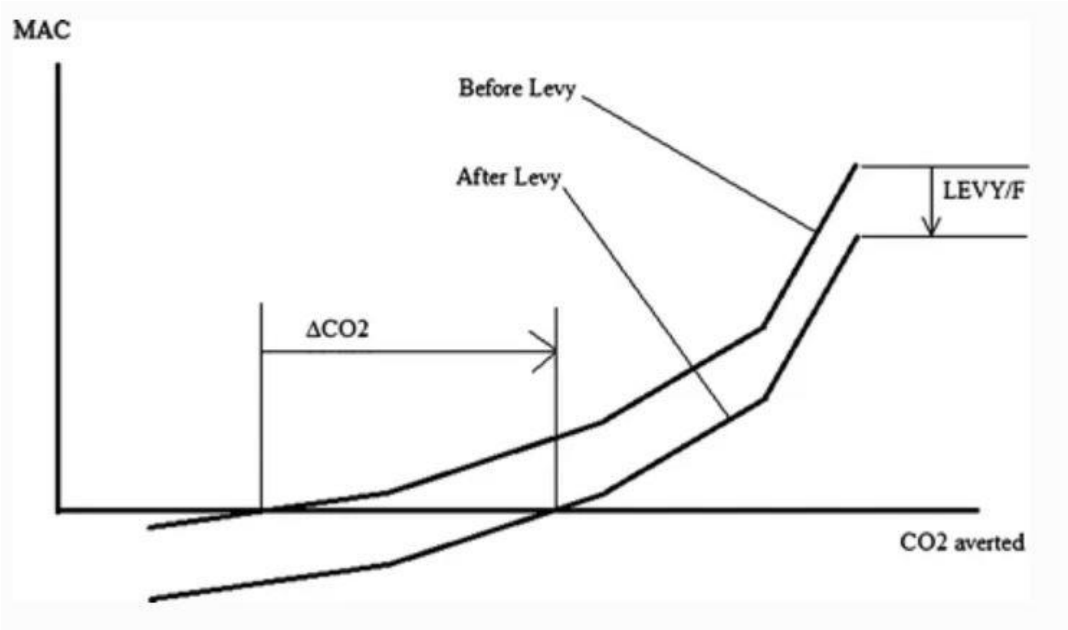

Figure 9

Using MACCs to determine the effect of a bunker levy (Psaraftis H. , 2012)

Nonetheless, the potential for CO_2 reduction can significantly vary among different measures. It is important to recognize that not all strategies or actions will yield the same level of reduction in CO_2 emissions, and it is crucial to consider the specific characteristics and attributes of each measure when analyzing their impact on CO_2 emissions.

It is important to note that the projected price of fuel is just one factor influencing MAC curves. Other variables, such as technological advancements, government policies, and market conditions, can also impact the cost of emission reduction measures. However, the price of fuel serves as a fundamental driver, influencing the overall shape and slope of the MAC curves.

By understanding the relationship between the MAC curves and the projected price of fuel, policymakers can make informed decisions about the most cost-effective approaches to addressing climate change.

3.3.1 The fuel factor

The relationship between fuel consumption and GHG emissions in the shipping industry is an undeniable and direct one. In essence, the more fuel a ship consumes, the greater the volume of greenhouse gases it emits. This relationship derives from the process of combustion that occurs within a ship's engine.

The direct relationship between fuel consumption and GHG emissions is the basis for many environmental regulations and initiatives within the maritime sector. Regarding carbon pricing implementation and effectiveness, certain aspects of fuels are worth outlining.

Fuel costs, especially in the shipping industry, can be significantly influenced by social and political situations, leading to a degree of uncertainty that makes quantification of cost changes challenging. Fuel is often sourced from regions that may experience political instability, armed conflict, or policy changes. These can disrupt production and supply chains, leading to fluctuations in fuel prices. For instance, political tensions in the Middle East, a significant source of global oil supply, often lead to spikes in oil prices. Furthermore, governmental policies, such as changes in tax regimes, subsidies, or environmental regulations, can have significant impacts on fuel prices. For example, the implementation of IMO 2020 led to a sudden price hike for low-sulphur marine fuels.

Other socioeconomic factors, such as changes in global economic growth rates, industrial production levels, and consumer behavior, can influence the demand for fuel and thus its price. The recent COVID-19 pandemic and its effect on global demand are an apt example of this. Considering these factors, predicting changes in fuel costs is indeed difficult due to the large number of variables and the unpredictable nature of social events.

In the *Fourth IMO's GHG Study 2020* (IMO, Fourth GHG Study, 2020) a sensitivity analysis of conventional fuels in 2030 was conducted, where the CO_2 abatement potential of a base line fuel price was compared to a fuel price increased by 100% and one reduced by 50%. It becomes evident that the more expensive conventional fuels are, the more cost effective becomes to turn to alternative technologies (Figure 10).

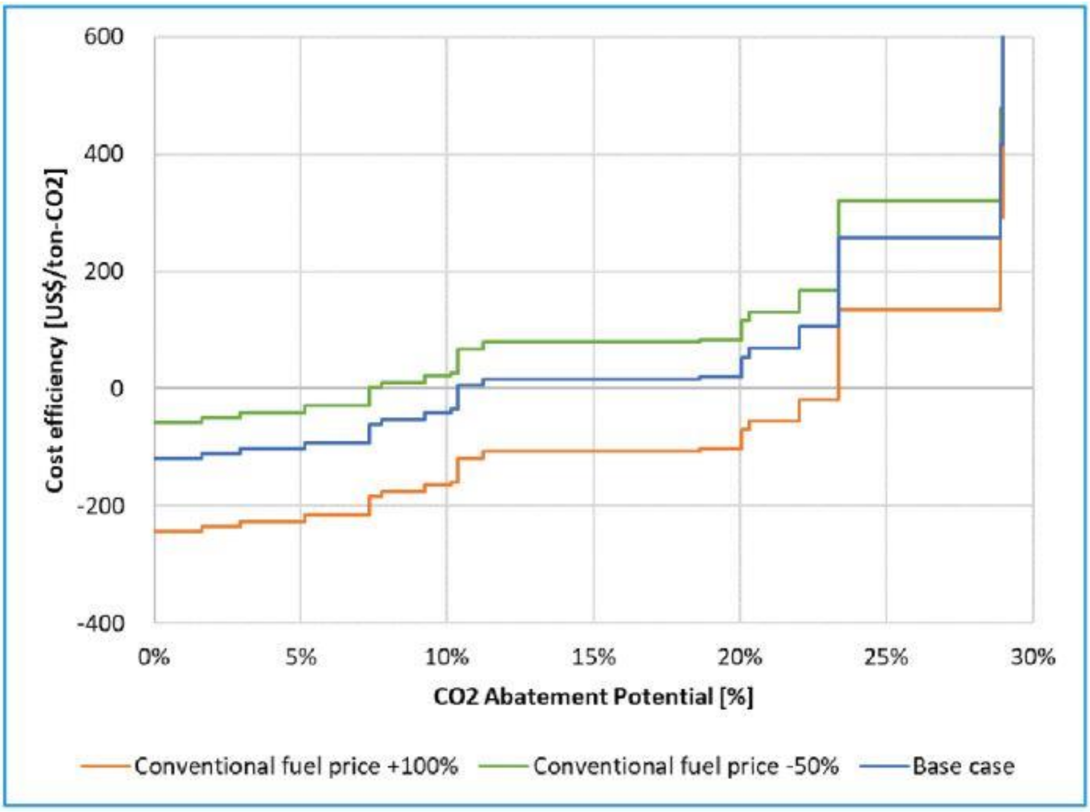

Figure 10

Sensitivity analysis of conventional fuel price in 2030 (IMO, 2020)

This is further validated by reviewing the sensitivity analysis of applying speed reduction by 10% in 2030, compared to three different price range of conventional fuel oil (Figures 11 & 12) (IMO, Fourth GHG Study, 2020).

CO_2 reduction potential	MAC (USD/tonne)		
	Fuel Price 188 USD/Tonne	Fuel Price 375 USD/Tonne (Base)	Fuel Price 750 USD/Tonne
Additional ship 0%	-62	-124	-248
Additional ship 50% (Base case)	79	17	-107
Additional ship 100%	219	157	33

Figure 11

Cost efficiency and abatement potential of Speed reduction by 10% in 2030 (IMO, 2020)

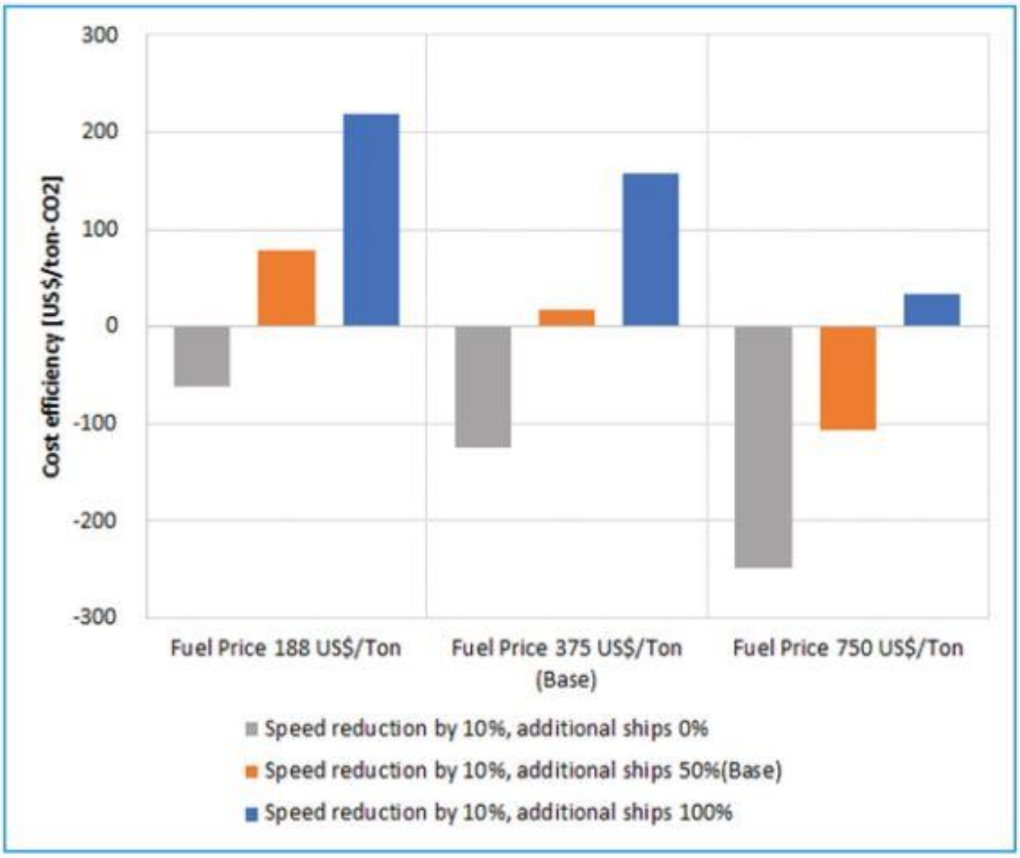

Figure 12

Sensitivity analysis of speed reduction by 10% in 2030[4] *(IMO, 2020)*

Escalating fuel prices and their inherent volatility make alternative approaches to CO_2 emissions reduction more economically viable in the maritime sector. In such circumstances, MBMs, such as bunker levies or emissions trading systems, become vital. By attaching a price tag to carbon emissions, the industry is motivated to explore and adopt cost-effective emission reduction strategies, accelerating the transition towards a low-carbon shipping industry.

Shipping companies, and indeed any industry with significant fuel costs, must build a degree of flexibility and resilience into their business models to accommodate uncertainties associated with fuel costs. By doing so, they can better withstand and respond to

[4] The percentage represented by additional ships refers to the relationship between the number of newly constructed vessels and the supplementary ships needed to maintain the total volume of freight transport, while changes in the overall transport volume are not considered in this calculation (IMO, 2020).

fluctuations, volatility, and other unpredictable factors. This adaptability allows companies to adjust their strategies, operations, and investments to mitigate the potential adverse effects of fuel cost variations and maintain long-term viability.

3.4 PUTTING A PRICE ON CARBON EMISSIONS

Carbon pricing is a strategy that puts a price on carbon emissions to incentivize businesses and individuals to reduce their carbon footprint. It is based on the principle that if the cost of emitting carbon is higher, businesses and individuals will be more likely to adopt low-carbon alternatives. By putting a price on the social costs of carbon, which is the drawback of using fossil fuels, carbon pricing corrects this market inefficiency. Producers could be given a larger incentive to put money into low-emission production elements if the associated costs of carbon were fully priced. Buyers would also be more motivated to purchase low-emission goods (Forum & International Transport Forum, 2021)

Carbon pricing in shipping represents a transformative economic instrument designed to account for these externalities by motivating greener practices, and pushing towards an environmentally responsible and sustainable maritime future.

There are several proposed options for carbon pricing in the shipping industry, the main being the following:

- **Carbon Levy or Tax:** This is a direct price on carbon emissions per tonne emitted by ships. It incentivizes shipping companies to reduce their CO_2 emissions to minimize their tax costs. It could also come in the form of a global mandatory contribution scheme: here, shipping companies would pay a set amount for every tonne of fuel they purchase or consume. The proceeds could be directed into a global fund aimed at financing emission reduction measures within the sector.
- **Emissions Trading System:** This involves a cap-and-trade system where the total permissible emissions from the shipping sector are capped, and allowances or permits are issued that equate to this cap. Companies are issued allowances for their emissions, which they can trade on the open market, creating a market-based approach to reducing emissions. Those that emit more must buy allowances from those that emit less, thereby

encouraging companies to reduce their emissions to avoid purchasing additional allowances.

- **Hybrid Systems:** Some proposals suggest a combination of the above systems, where certain aspects of different carbon pricing systems are merged to form an optimized solution.

Still, implementing any of these options on a global scale is complex, due to factors such as the international nature of the shipping industry, its multifaceted nature, and the necessity for widespread cooperation and compliance. Hence, on a global scale, it is a subject of ongoing discussion among policymakers, shipping companies, and environmental organizations. It's a fine balance to strike – implementing effective measures to reduce carbon emissions in the shipping industry without unfairly disadvantaging certain nations or companies.

However, on a regional level, some radical initiatives have been put forth. The European Union is including shipping in its Emissions Trading System by 2024. These regional initiatives, while promising, also highlight the need for a coordinated global approach. Without such coordination, there's a risk of creating a patchwork of different schemes, which could complicate compliance and potentially distort shipping routes and markets. This emphasizes the important role of international bodies like the International Maritime Organization in coordinating and implementing MBMs for the shipping industry.

3.4.1 Emissions cap-and-trade schemes

A cap-and-trade system sets a limit or “cap” on the total amount of greenhouse gases that can be emitted by industries covered by the system. This cap is usually reduced over time to decrease overall emissions.

Companies within these industries are given emission allowances, which represent the right to emit a certain amount of greenhouse gases. The total amount of these allowances matches the cap. These allowances can be bought, sold or traded between companies, hence the name “cap-and-trade”. This trading allows companies with more efficient operations or technology to sell their excess allowances to companies that are less efficient or that find it more cost-effective to buy allowances rather than reduce their own emissions (Figure 13).

If a company's emissions exceed their allowances, they are required to purchase additional allowances from other companies or through a central marketplace. This requirement incentivizes companies to reduce their emissions in the most cost-effective way possible.
Over time, as the cap is gradually lowered, the total emissions from the industries within the scheme are reduced (Figure 13). This system allows for flexibility in how reductions are achieved, encourages innovation, and ensures that emissions are reduced in a cost-effective manner.

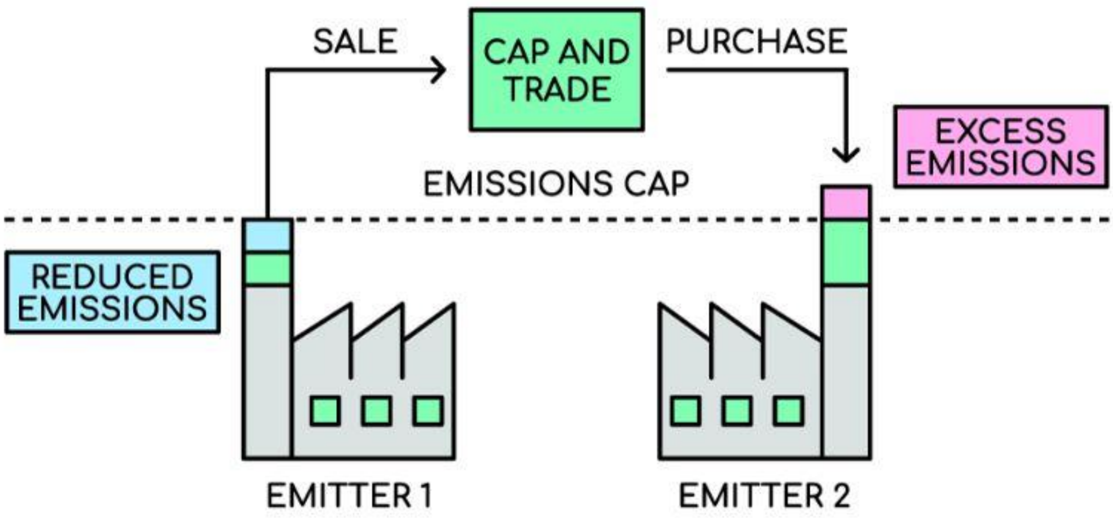

Figure 13
The Cap-and-trade system (CLIMEON, 2023)

There's been a noticeable rise in global backing for carbon pricing, though there's considerable variability in terms of the degree of implementation, associated costs, and coverage across different regions. At present, there are 28 operational Emission Trading System programs worldwide, with an additional 21 in varying phases of preparation and implementation (ICAP, 2023). These initiatives span across an array of geographic and economic contexts, including supranational, national and subnational scales. They encompass various sectors, such as heavy industry, transportation, buildings and power generation.
Among these carbon markets, several have been in operation for close to two decades, demonstrating resilience by successfully navigating major crises. A prime example of a

successful ETS is the European Union Emissions Trading System (EU ETS), the first and largest system of its kind in the world. The EU ETS operates in the 27 EU countries, as well as Iceland, Liechtenstein and Norway, and it covers approximately 45% of the EU's greenhouse gas emissions (EPA, 2023).

The EU ETS showcased remarkable resilience by weathering the 2008 global economic crisis and its subsequent financial repercussions. Since then, numerous reforms have been implemented to strengthen its capacity to withstand future crises, and these measures have resulted in a more resilient system. This approach has been mirrored by other ETS initiatives worldwide, including those in California, New Zealand, South Korea, and various provinces in China.

These protective measures were put to the test during the COVID-19 pandemic at the start of this decade. Nevertheless, these markets responded as anticipated and have shown remarkable resilience in the face of such challenges, maintaining stability throughout (ICAP, 2023).

3.4.1.1 EU ETS

In an effort to address the climate crisis and achieve its ambitious environmental targets, the European Union has been reassessing and updating its pre-existing climate policies. The ETS was inaugurated by the EU in 2005, marking the world's first venture into the field of emissions trading systems. Over the years, it has remained the largest greenhouse gas emissions trading system, encompassing multiple countries and multiple sectors (European Commission, 2023).

Recently, the EU has proposed expanding the scope of the ETS to encompass the maritime industry. This strategic move aims to diminish the overall emissions footprint of the shipping sector, thereby bolstering the likelihood of attaining the EU's *Fit for 55* policy, as well as its objective of achieving climate neutrality by 2050.

Under the expanded EU ETS, which is anticipated to be progressively implemented for shipping over the next three years, vessels will be obligated to disclose 50% of their tank-to-wake CO_2 emissions on voyages entering or leaving the European Economic Area (EEA), and a full 100% of their CO_2 emissions on voyages between and within EEA ports (Figure 14). These emissions, once reported, will subsequently need to be verified and compensated for through the EU MRV system (ClassNK, 2023).

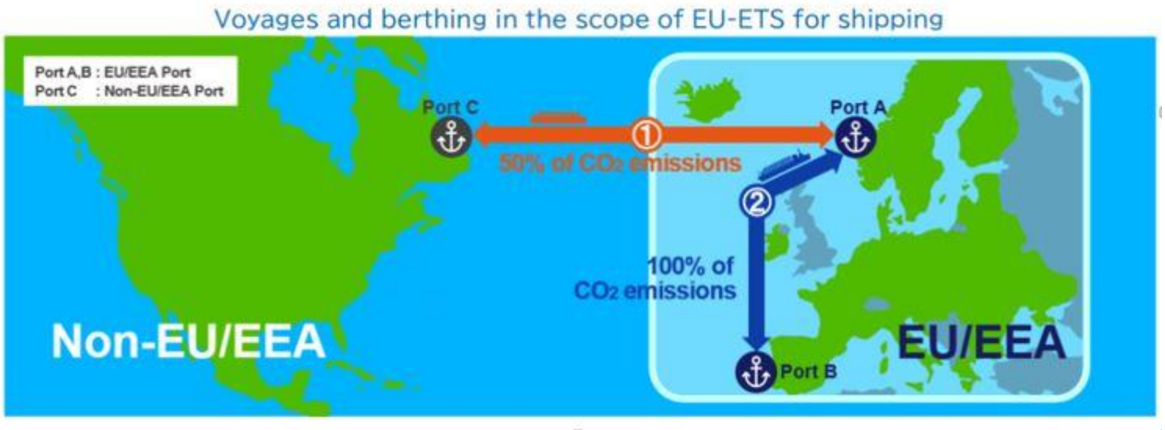

Figure 14

The scope of the EU ETS for shipping (ClassNK, 2023)

The new regulations will primarily affect passenger and cargo ships with a gross tonnage exceeding 5,000. Beginning in 2024, such ships will fall under the jurisdiction of the EU ETS. The payment obligations for reported emissions will be phased in over a span of three years. In 2025, vessels will have to pay for 40% of the verified reported emissions for 2024. In 2026, they will need to pay for 70% of the verified reported emissions for 2025. By 2027, they will be required to pay for 100% of the verified reported emissions for 2026 (Figure 15).

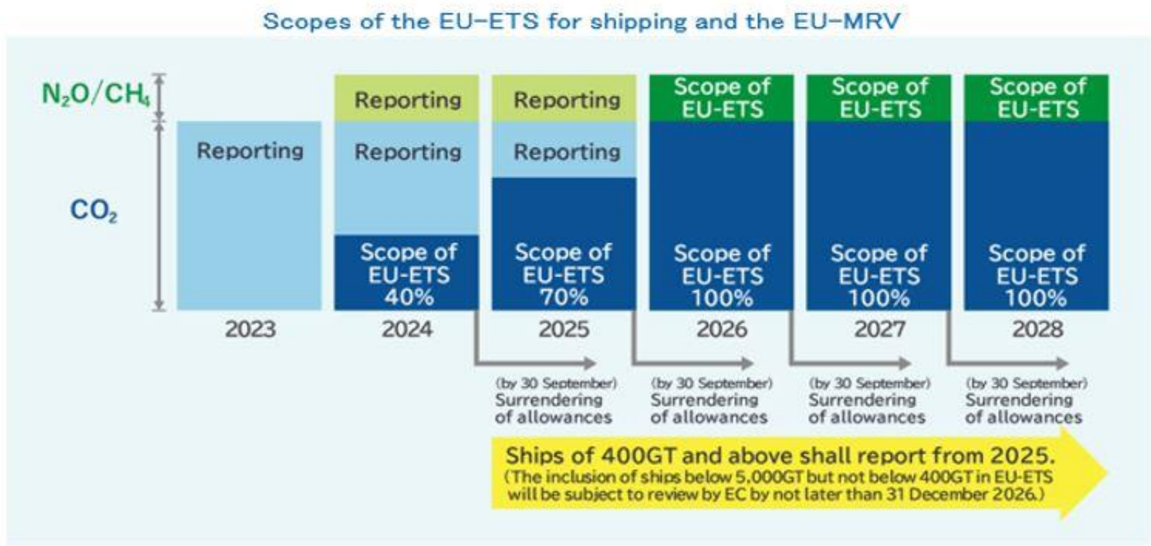

Figure 15

The timeline for the scopes of the EU ETS for shipping and the EU MRV (ClassNK, 2023)

Notwithstanding, the implementation schedule will vary for other ship types and sizes. Offshore service vessels with a GT above 5,000 will be incorporated into the Monitoring, Reporting, and Verification regulation in 2025, and the EU ETS in 2027. Other ships, with a GT of 400 and above, will be included in the MRV in 2025, with a review scheduled for 2026 to consider their inclusion in the EU ETS.

Beyond the inclusion of CO_2 emissions, it has been agreed that from 2024 methane and nitrous oxide emissions will also be encompassed within the MRV regulation, and they will be included in the EU ETS from 2026. This expansion of the ETS further demonstrates the EU's commitment to addressing a broad range of greenhouse gases and highlights its comprehensive approach to mitigating climate change.

The EU is in the process of implementing stringent non-compliance penalties associated with its ETS. Shipping companies that fail to surrender the necessary allowances for their greenhouse gas emissions in due time will face an excess emissions penalty. The financial penalty amounts to 100€ for each tonne of CO_2 equivalent that has not been surrendered by the specified deadline. Furthermore, should a shipping company repeatedly fail to surrender allowances for two or more consecutive reporting periods, the EU has the power to issue an expulsion order against the non-compliant vessels. This expulsion order carries significant implications; ships can be detained by the Member State they are flagged in and even be denied entry into ports under the jurisdiction of another Member State (Norton Rose Fulbright , 2023). In extreme cases, if a vessel consistently fails to comply with the MRV obligations over two or more consecutive years, it may be denied the privilege to trade in the EU or face expulsion (DNV, 2019).

The term “Port of call” is defined as the port where a ship stops for cargo-related activities or crew changes (ClassNK, 2023). However, stops exclusively for refueling, obtaining supplies, making repairs, distress situations and adverse weather, or search and rescue activities are not considered as port calls. Additionally, container ships stopping at neighbouring container transshipment ports are excluded from the definition of the port of call under the EU ETS regulations. These transshipment ports are identified as those where the share of transshipment of containers exceeds 65% of the total container traffic during the most recent twelve-month period for which data are available and are located less than 300 nautical miles from a Member State port.

To ensure fairness and transparency, the European Commission will compile a list of non-EU container transshipment ports situated within 300 nautical miles of an EU port by the 31st of December, 2023. The purpose of this list is to circumvent evasive port calls, as these transshipment ports will be excluded from the "Port of call" concept. Thus, shipping companies will need to account for 50% of their emissions arriving in these transshipment ports, in addition to the leg from the transshipment port into the EU. This list will be updated biennially (Verifavia Shipping, 2023).

Lastly, the EU ETS includes provisions for shipping companies operating ice-class ships. Until December 31st, 2030, vessels, with the ice class IA, IA Super, or an equivalent ice class, can surrender 5% fewer allowances than their verified emissions. This provision underscores the EU's nuanced approach to considering the unique challenges faced by different types of vessels in its bid to reduce greenhouse gas emissions.

The introduction of the EU ETS is seen by many as an opportunity. It could stimulate secondary trading of allowances, or inspire entities to accelerate their decarbonization efforts in order to purchase fewer allowances. Nonetheless, the administrative and financial burden of the scheme, along with the commercial implications it introduces, cannot be overlooked. Navigation through these regulations requires a thorough understanding of the directives, a keen commercial perspective, and carefully crafted charterparty clauses. This necessitates cooperation between commercial entities, including ship owners and charterers. Particularly as parties adapt to the administrative nuances of the EU ETS, this cooperative approach may present challenges.

3.4.1.1.1 The Commercial Operator's Liabilities

The European Union also highlights the complexity of allocating responsibility for emissions-related decisions in the shipping industry. Decisions pertaining to factors that directly impact emissions, such as the choice of fuel, and the route and speed of a ship, may often be taken by entities other than the Shipping Company. The European Union Directive suggests that individual Member States should institute national legislation to place the financial responsibility for emissions on the commercial operators of vessels. This recommendation is in keeping with the "polluter pays" principle, a tenet that seeks to assign the costs of pollution to those who cause it. By doing so, the law aims to harmonize the interests of various stakeholders, as discussed in the preceding chapter, by attributing the liabilities to the actual polluters. This approach ensures that those responsible for pollution have a direct financial incentive to reduce emissions, thus promoting a cleaner and more sustainable maritime sector.

In the current absence of such legislative measures, it is advised that ship owners and charterers proactively negotiate contractual terms to deal with the allocation of these costs. BIMCO, the world's largest international shipping association, has preemptively produced an *ETS – Emissions Trading Scheme Allowances Clause for Time Charter Parties*. This clause underlines the need for parties to carefully consider the implications of the EU ETS on their operations. As part of these considerations, entities need to determine how the costs of compliance with the EU ETS might be passed along their supply chains to their customers and the potential implications for their commercial operations. Furthermore, practical issues, such as resolving disputes about operational decisions affecting a vessel's emissions and ensuring the costs of allowances are covered even if a fixture ends well before the surrender date of allowances, need to be addressed.

The BIMCO Clause embodies the "polluter-pays" principle, ensuring ETS costs are transferred to the commercial operators of the vessels – specifically, the time charterers in this case. The underlying premise of this clause necessitates cooperation and collaboration between both parties to the charter party, and it entitles the shipping company to pass on the ETS costs to the charterer, regardless of the type of contract. Consequently, it underscores the need to embed in national law the shipping company's right to claim reimbursement for costs incurred from the surrender of allowances. This legal framework would support equitable cost distribution in compliance with the EU ETS.

3.4.2 Carbon Tax and Feebate System

Emission taxes and levies[5] function as financial tools that impose a predetermined price on either the consumption of fossil fuels, or the emission of carbon dioxide or other greenhouse

[5] While the terms *tax* and *levy* are frequently used as synonyms, they have different implications when it comes to the funds they produce. A tax creates revenue that is not allocated for a particular use and is received by the governing state. In contrast, the income generated by a levy is reserved for a specific objective (Baresic, 2022).

gases. These economic mechanisms compel market participants to pay according to their emission levels, thus making the use of fossil fuels cost more.

The cost of greenhouse gas emissions under a tax or levy system is determined politically, with a set price for a fixed duration known to the payers. However, it does not guarantee a certain reduction in greenhouse gas emissions, thereby making the attainment of specific environmental goals uncertain. To ensure an emissions tax or levy is productive, it is critical to establish a price that will sufficiently incentivize reductions in emissions to align with the desired environmental outcome.

A system that involves regular assessment and revision of the tax or levy rate could enhance the probability of achieving environmental targets. However, this might lead to a decrease in business predictability since shipping companies cannot foresee how the tax or levy will fluctuate over time. This uncertainty is significant, as the anticipation of future carbon prices is fundamental in formulating the business justification for zero-emission investments.

Implementing price corridors, which establish a range of minimum and maximum carbon prices, could potentially mitigate some of the uncertainties surrounding future carbon pricing. This strategy could reduce investment risks, thereby encouraging the shift to alternative fuels and energy sources.

A *feebate* system, a combination of *fee* and *rebate*, is a variation of the tax/levy approach. In this structure, a standard for carbon or emissions intensity is established, which could remain static or progressively tighten over time to further encourage zero-emission shipping activities. Participants, such as ship owners/operators, who exceed the set standard are subject to fees, while those who emit below the threshold are granted rebates funded by the collected fees. Hence, vessels with high emissions of carbon intensity face penalties, while those with low emissions receive rewards (Baresic, 2022).

This feebate mechanism promotes continuous advancements in carbon intensity, fosters investments in zero-emission fuels and technologies, and encourages more efficient operations. As such, it stimulates innovation while also reducing emissions (Figure 16). However, like taxes or levies on emissions, it cannot guarantee the achievement of specific environmental targets. The success and environmental efficacy of feebates largely depend on the regulator's ability to properly set a benchmark fee and rebate.

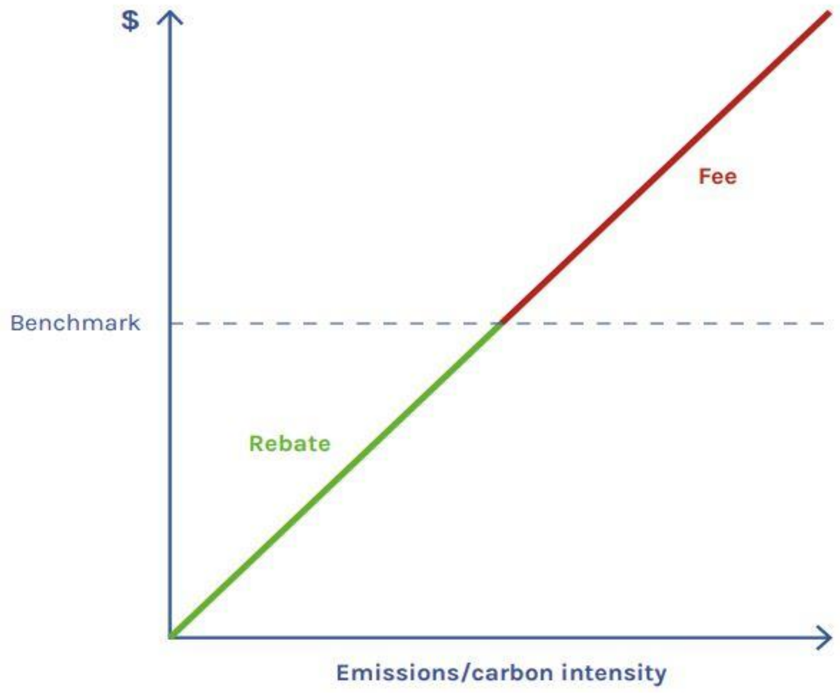

Figure 16

The feebate mechanism, (Baresic, 2022)

Moreover, there could be a higher degree of uncertainty in meeting specific absolute emission reduction targets if the system is based on carbon intensity. Feebates could also contribute to, or worsen, a two-tier market situation: low- or zero-emission vessels would benefit from rewards while high-emission vessels would face penalties. This could make it more challenging for high-emission vessels to invest in the necessary upgrades to meet the required standards. Consequently, some owners might find themselves paying fees while simultaneously trying to invest in alternative technologies or fuels, which can present a substantial financial burden (Baresic, 2022).

3.4.2.1 FuelEU

The FuelEU Maritime regulation is yet another crucial part of the European Union's *Fit for 55* package, aiming to set the EU on the right path to becoming climate-neutral by 2050. The FuelEU Maritime regulation operates in tandem with EU ETS, each targeting distinctive angles of the maritime decarbonization process. While ETS creates incentives for energy conservation by placing a cost on carbon emissions, FuelEU regulation primarily focuses on promoting advancements in fuel technology. In the short to medium term, the pricing signals emitted by ETS may not adequately spur the evolution of fuel technologies; this gap is addressed by the FuelEU Maritime regulation. Hence, both regulations complement each other in fostering a wholesome approach towards the shipping industry's transition to a low-carbon future (European Commission, 2022). Upon its implementation on January 1st, 2025, it will escalate the proportion of renewable and low-carbon fuels within the fuel mix of the EU's international maritime transport.

The commission proposes that to encourage the uptake of sustainable maritime fuels, a restriction should be placed on the carbon intensity of energy consumed on marine vessels. The proposal, therefore, introduces a maritime fuel standard, advocating for the adoption of low-carbon fuels by setting upper limits on the carbon intensity of utilized energy. Furthermore, it mandates that the ships with the highest carbon intensity use onshore power during their docking periods in EU ports. The shipping companies will be held accountable for adhering to these regulations.

Beginning in 2025, reductions in the annual mean GHG intensity of on-board energy usage will be initiated, with a preliminary 2% improvement relative to the baseline data from 2020. This requirement will incrementally tighten over time, necessitating a 6% advancement by 2030 and an ambitious 80% reduction by 2050 (Figure 17).

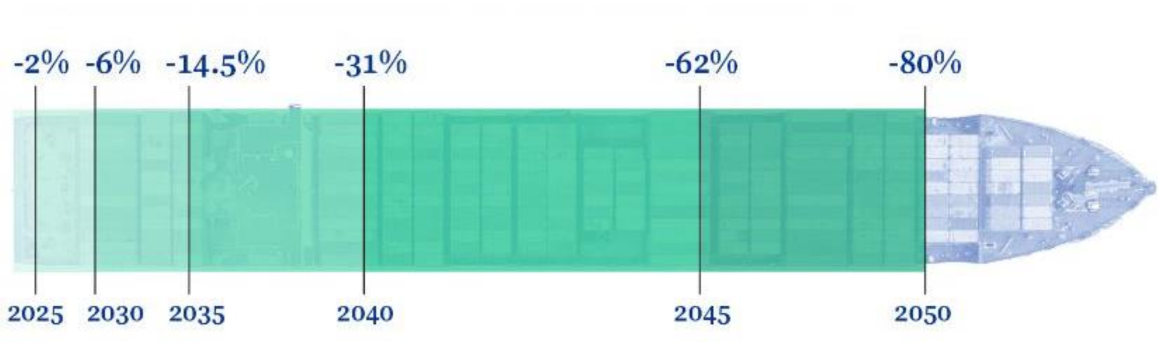

Figure 17

FuelEU: Annual average carbon intensity reduction compared to the average in 2020 (European Council, 2023)

This proposal applies to all energy consumed onboard a ship operating in or between EU ports. However, only 50% of the energy used by ships embarking or departing EU ports for journeys to or from third countries is applicable. This regulation applies to commercial vessels exceeding 5,000 gross tonnes, without regard for their flag of origin. The proposal adopts a well-to-wake lifecycle methodology to calculate CO_2 emissions equivalents, encapsulating methane and nitrous oxides, arising from energy use.

Shipping companies will bear the responsibility for regulatory compliance. The new fuel standards will be applicable not just to vessels using fuels procured within the EU, but also to those utilizing fuels acquired outside the EU jurisdiction. The proposal incorporates a method for the lifecycle analysis of fuels and principles for fuel monitoring, reporting, verification, and accreditation. This proposed system is designed to operate separately from, but in addition to, the existing EU MRV system and should be designed to complement the existing EU THETIS[6] reporting database. Vessels will be required to hold a valid FuelEU compliance certificate.

Furthermore, from January, 2030 onwards, the proposal mandates that cargo and passenger ships docking at EU ports for durations exceeding two hours must connect to an Onshore Power Supply (OPS), and must utilize this power for all energy requirements while docked, excluding emergency situations or vessels employing zero-emission technologies. Exemptions are permissible until the end of 2034 for vessels that are unable to connect to the OPS due to an absence of connection points in the port or incompatibility between the port installation and the on-board OPS equipment. However, this flexibility will be considerably reduced from 2035 onward.

Standardized penalties have been set for non-compliance with both the fuel standards and OPS requirements. Penalties or rewards based on a ship's or fleet's performance relative to its annual target will be estimated, with the cost of low-carbon fuel necessary to meet the target serving as the basis for this calculation. The collected penalty revenue will be channeled into the Innovation Fund to aid the production of renewable maritime fuels and other maritime sector greening activities.

Ship operators are afforded some flexibility through provisions for banking, borrowing, and pooling mechanisms as means to facilitate compliance with the set targets.

---

[6] The EU THETIS reporting database, developed by the European Maritime Safety Agency (EMSA), is an information system that supports the uniform implementation and enforcement of EU maritime legislation. It aids in monitoring compliance with various ship safety, security, and environmental regulations (EMSA, 2023).

Through the banking and borrowing mechanisms, maritime operators can manage their compliance balance over different reporting periods. If a ship has performed exceptionally well for one year and thus has a surplus of compliance credits, these credits can be "banked" for use in the subsequent reporting period. On the other hand, if a ship experiences a shortfall in compliance credits within a reporting period, it may "borrow" an advance of these credits from the next year to offset the deficit (Figure 18) (Bureau Veritas, 2023).

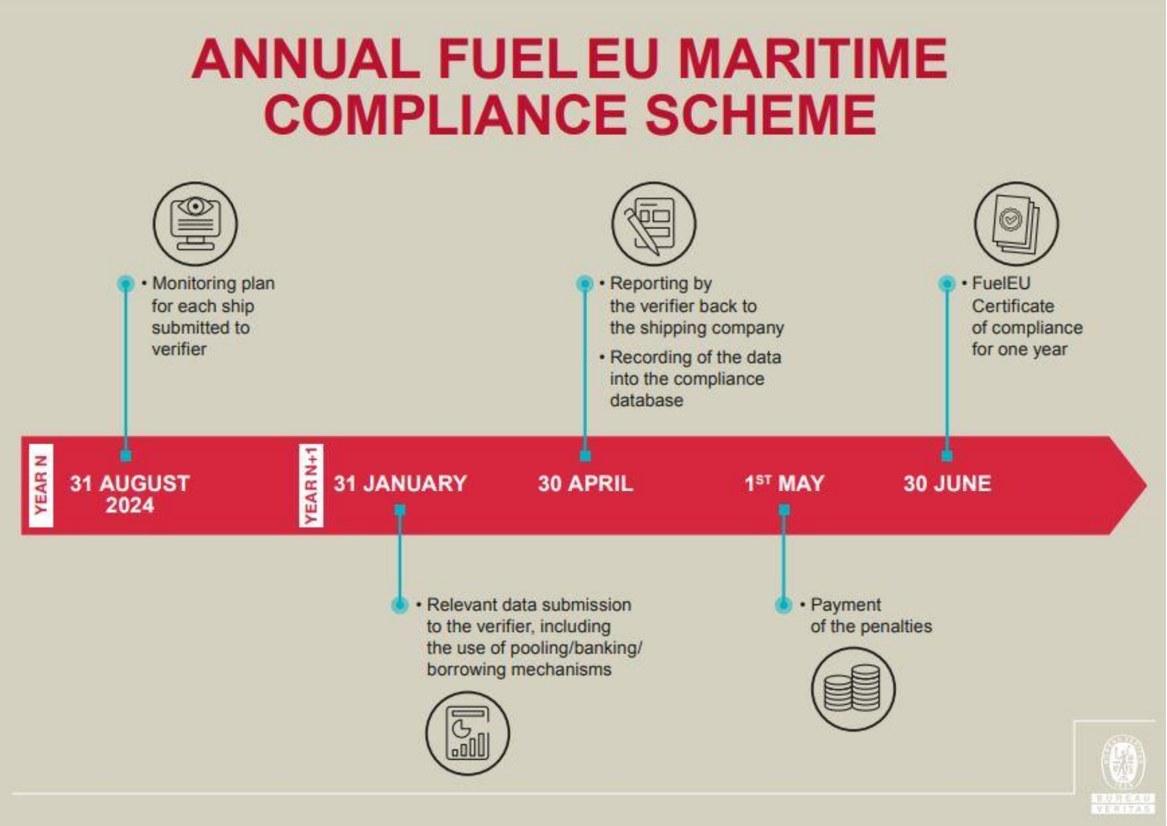

Figure 18

The FuelEU annual compliance scheme (Bureau Veritas, 2023)

Pooling and Averaging are another mechanism to facilitate compliance in the context of FuelEU Maritime regulation, by offering flexibility to vessels and shipping companies when it comes to meeting their greenhouse gas emissions reduction targets.

Averaging refers to the ability of a shipping company to balance the emissions across its fleet of ships. If one ship is unable to meet the emission reduction target but another ship in the same fleet overachieves the target, the average emission reduction across the fleet might still meet the required target. This mechanism allows shipping companies to gradually implement changes across their fleet rather than having to ensure each individual vessel meets the targets independently.

Similarly, Pooling allows two or more ships, possibly owned by different companies but verified by the same body, to combine their emissions performance. In a similar manner to averaging, if one ship falls short of the target but another overachieves, the combined or "pooled" performance could still meet the required standards. This provides an opportunity for collaborative compliance and can create incentives for companies to invest in greener technologies. These measures are designed to provide a level of flexibility for companies in achieving their targets, recognizing that transforming the maritime sector towards greener operations is a complex and gradual process.

At an initial examination, it might be presumed that EU ETS, which aims to cover 100% of the designated 2026 emissions by 2027, will exert a more substantial influence compared to other mechanisms. FuelEU Maritime, on the other hand, only targets a modest percentage of emissions, even by 2035. However, an in-depth assessment by Lloyd's Register, indicates that by 2035, the economic implications of FuelEU Maritime could already surpass those of the EU ETS (Lloyd's Register - LR, 2023). By 2050, the costs incurred from FuelEU Maritime penalties could be six to eight times larger than the expenses related to acquiring European Union Allowances (EUA) (Figure 19).

While EUA costs can be mitigated through more efficient vessel operations, the risk of incurring FuelEU Maritime penalties can only be substantially mitigated by shifting fuel technologies. Furthermore, FuelEU Maritime distinctively rewards those who adopt early by progressively reducing the additional benefits gained from exceeding compliance over time, while simultaneously escalating the penalties for not achieving the predetermined target. Comprehending the distinctive significance of each strategy, as well as pinpointing the most appropriate approaches and scheduling for compliance, is a fundamental first step in skillfully navigating the intricacies of carbon pricing (European Commission, 2022) (European Council, 2023) (Bureau Veritas, 2023) (DNV, 2022) (Lloyd's Register - LR, 2023).

The European Parliament, the Council of the European Union, and the European Commission have agreed upon the FuelEU Maritime regulation. The regulation was formally adopted in 25th July 2023.

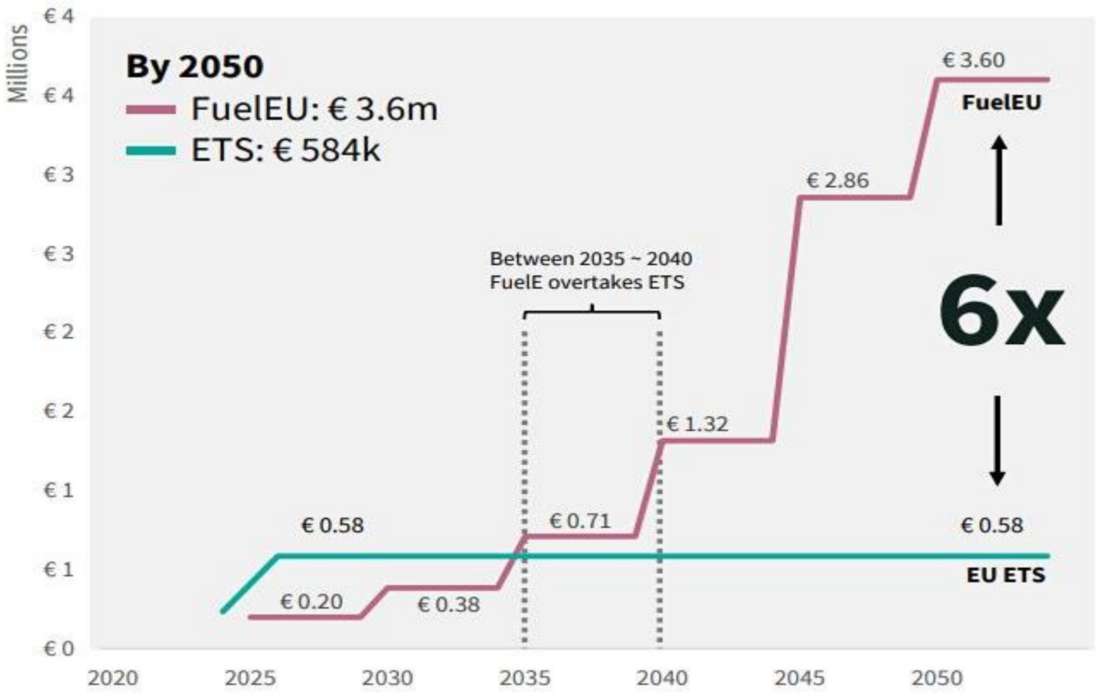

Figure 19

EU ETS and FuelEU maritime cost comparison (Lloyd's Register - LR, 2023)

3.4.2.1.1 Lifecycle GHG emissions

From 2025 onwards, the adoption of FuelEU, as well as the revised IMO's GHG Strategy, will trigger a significant shift in the maritime industry's approach towards reducing greenhouse gas emissions. Two of the immediate, consequential effects will be the development of robust certification systems for marine fuels and an intensified focus on calculating lifecycle greenhouse gas emissions (DNV, 2022).

An important concept here is the "well-to-wake" lifecycle assessment. This comprehensive approach accounts for the greenhouse gas emissions produced across the entire fuel supply chain. It includes not only the direct emissions from burning the fuel onboard the ship, also referred to as "wake" or "ship" emissions, but also the emissions generated during the extraction, processing, and transportation of the fuel, collectively known as "well" or "upstream" emissions (Figure 20) (Bureau Veritas, 2023).

The incorporation of this well-to-wake lifecycle approach in FuelEU Maritime regulation signifies a substantial transformative change in the pursuit of climate targets. It provides a more holistic and accurate representation of the environmental impacts associated with different types of fuels, highlighting the often overlooked aspects of fuel production and use.

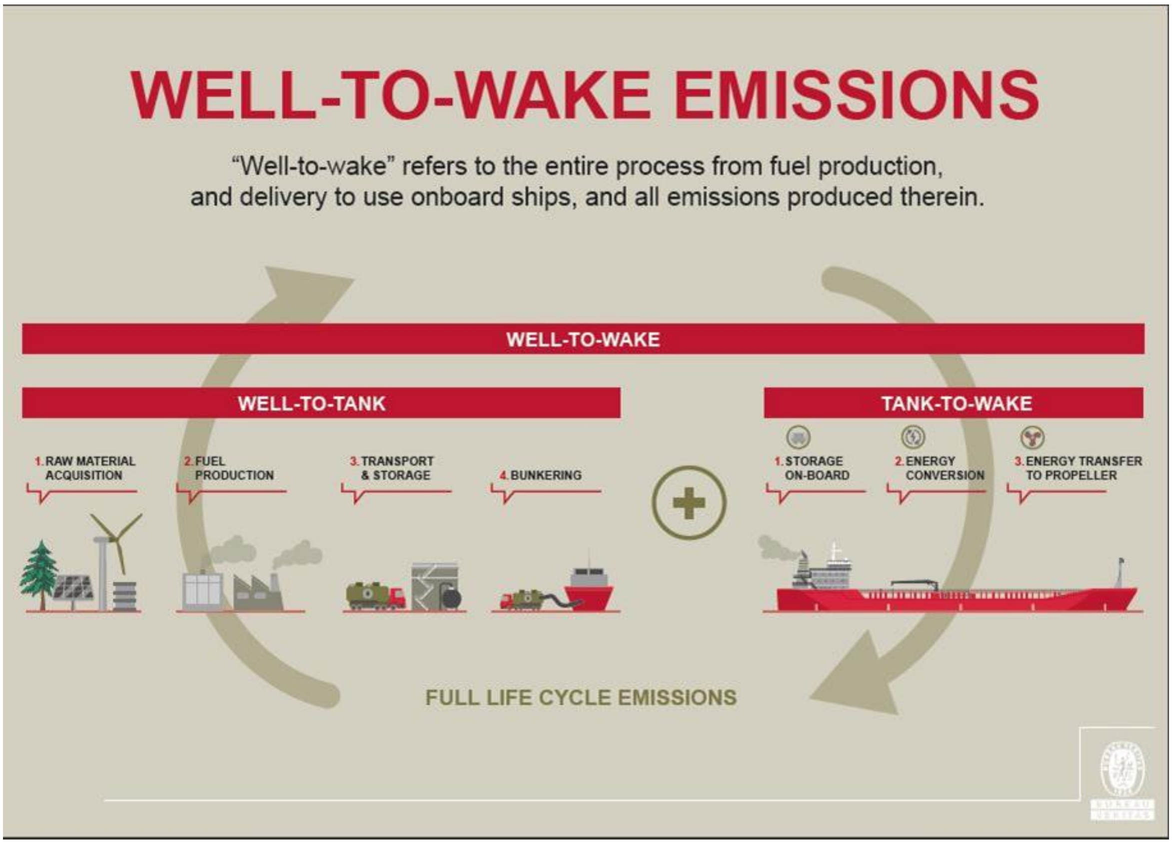

Figure 20

Well-to-Wake infographic (Bureau Veritas, 2023)

This comprehensive understanding is critical as it forms the foundation for the development of effective and targeted mitigation strategies. Policymakers and industry leaders, equipped with this nuanced knowledge, can design strategies addressing the entire spectrum of emissions associated with maritime fuels. This fosters a greener and more sustainable maritime industry in line with the FuelEU Maritime regulation's objectives.

Meanwhile, the ongoing international discussions on advancing preliminary guidelines for lifecycle greenhouse gas and carbon intensity related to marine fuels hold significant importance. Recognizing the necessity for increased efforts, IMO has established a dedicated correspondence group to focus on the lifecycle GHG analysis of marine fuels. This group's primary role is to develop pertinent guidelines to be adopted by the IMO, serving as a blueprint for managing the environmental impact of marine fuels. The diversity of potential low-carbon and zero-carbon fuels for shipping, with their varying production pathways – such as distinct generations of biofuels, hydrogen-based fuels, and more – results in substantial differences in their overall environmental footprint.

Facilitating an effective transition towards these alternative low- and zero-emission fuels necessitates the creation of a rigorous international framework. This framework should be geared towards assessing the greenhouse gas intensity and sustainability of these fuels in a methodical and holistic way. This comprehensive approach ensures that the evaluation is not just focused on the emissions at the point of use, but includes the entire production and distribution process, providing a complete picture of each fuel's environmental impact.

A key feature of these proposed guidelines is the Lifecycle Assessment (LCA) methodology. LCA enables a comprehensive well-to-wake calculation, encompassing both well-to-tank and tank-to-wake emission factors. This inclusive estimation of total GHG emissions associated with the production and use of alternative marine fuels will significantly aid the move towards more sustainable maritime practices. It will help identify potential areas of improvement and spur the development and adoption of low-carbon and renewable marine fuel options (IMO, 2022).

3.4.2.2 The *Fund and Reward* system by ICS

In preparation for the negotiations with IMO pertaining to the revision of the Initial Strategy and the introduction of a carbon pricing scheme for shipping on a global scale, ICS has put forth in-depth proposals supporting a Global Fuel Standard as a technical measure to reduce the GHG intensity of marine fuels. The strategy involves giving financial incentives to ships and energy manufacturers who choose to use low or zero-emission fuels. ICS presented its *Fund and Reward (F&R)* scheme to the International Maritime Organization, to spur the uptake of alternative fuels, which currently come with a higher price tag compared to traditional marine fuel (ICS, 2022) (ICS, 2023).

The proposed F&R system takes inspiration from several recent greenhouse gas reduction suggestions from various governments, along with a flat rate contribution model previously put forth by ICS and INTERCARGO, and the EU's recent global IMO measure suggestions. Rewards would be calculated based on the amount of CO_2 emissions avoided and funded by a mandatory contribution from ships per tonne of CO_2 emitted. The ICS hopes to launch this Fund and Reward scheme by 2024, subject to regulatory approval from the IMO (ICS, 2023).

The ICS recommends that an "International Maritime Sustainability Fund" should be established to collect contributions from the global fleet. The fund could potentially amass billions of dollars each year, which could be used to decrease the global price difference between high carbon marine fuels and alternative fuels, while also facilitating investment in developing countries to produce new marine fuels and bunkering infrastructure.

Ships would be rewarded based on annual reports of CO_2 emissions reductions achieved using eligible alternative fuels. For instance, a ship using ammonia (or methanol, hydrogen, sustainable biofuels and synthetic fuels) could see a cost reduction of over $1.5 million per year. The ICS aims to ensure that at least 5% of the world fleet's energy comes from alternative fuels by 2030.

According to a comprehensive impact assessment conducted by *Clarkson's Research* for the ICS, a financial contribution of up to approximately $100 per tonne of CO_2 emitted wouldn't result in disproportionately adverse impacts on nations' economies (ICS, 2022). However, the ICS suggests starting with lower contributions, which can be reviewed every five years as new fuels become more readily available.

The contribution's size from ships is crucial, especially for developing countries whose backing is necessary for the regulatory framework's approval. The framework's structure is based on the industry's prior proposals for an IMO Research and Development (R&D) Fund.

3.4.3 Tax vs ETS

Emissions Trading Systems and carbon taxes are two distinct mechanisms with a share objective. Both adhere to the “polluter pays” principle and place an explicit cost on carbon, motivating industries and consumers to account for a portion of the social cost of GHG emissions. This incentivizes low-carbon alternatives, influences consumption habits, and bolsters low-carbon investments. Rather than dictating specific emissions reduction actions, a carbon price allows individuals and firms to decide the most effective response. Consequently, both ETS and carbon taxes can facilitate more cost-effective emissions reductions than other climate policies.

A carbon tax, similar to other taxes, generates public revenue while dissuading polluting behavior. Similarly, an ETS that auctions off allowances can also produce income. This income can be utilized to support social programs, advance climate and energy projects, improve infrastructure, facilitate tax reforms, and stimulate technological innovations (ICAP, 2021).

On the one hand, ETS operates on the principle of setting a firm limit on total allowable emissions. By doing so, it ensures a specific outcome in terms of emissions reduction, effectively quantifying the environmental impact of the policy (Figure 21). This cap signifies the total emissions permissible, establishing a tangible environmental goal for the industries covered. The price of carbon, defined by the cost of an emission allowance, isn't predetermined but relies on market dynamics. It's governed by supply and demand: as the demand for allowances rises or falls based on economic activity and the emissions generated, the price of carbon correspondingly fluctuates.

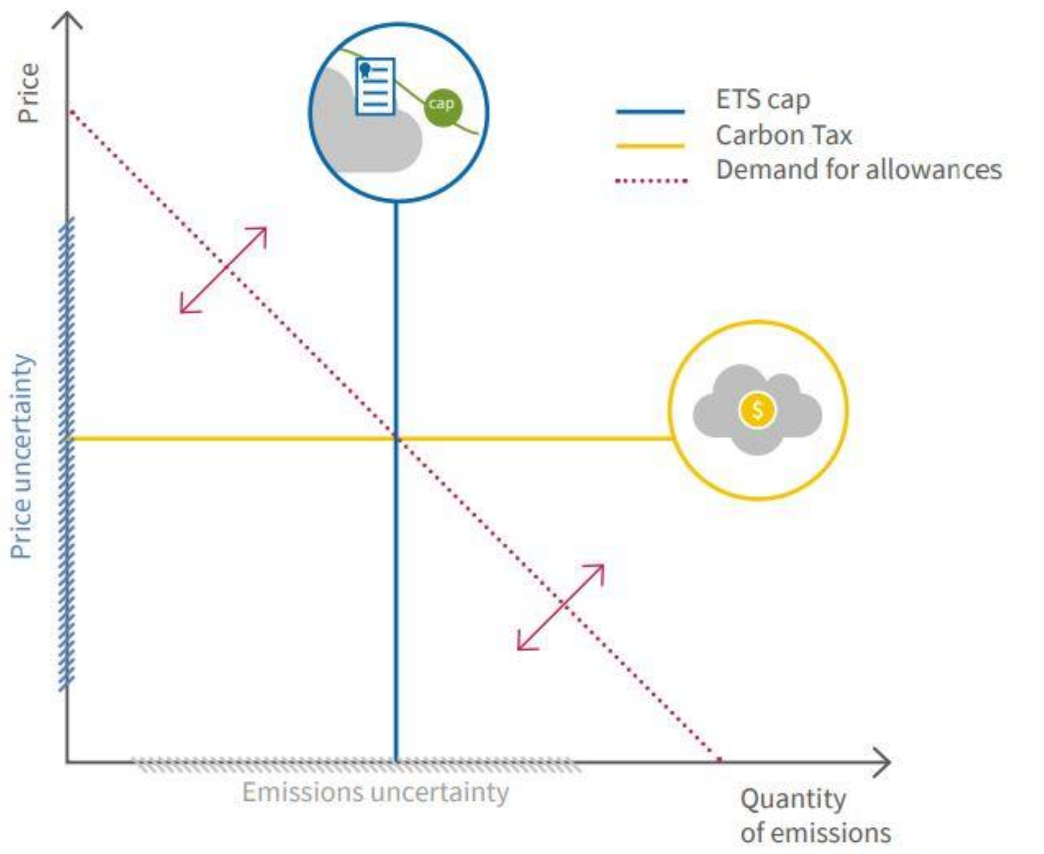

Figure 21

Price Certainty versus Quantity Certainty (ICAP, 2021)

The benefit of this market-based approach is its inherent flexibility, which allows companies to opt for the most economically viable route to curb emissions. That said, this approach also introduces a layer of financial risk due to the potential volatility in the price of carbon. Companies must, therefore, strategize effectively to manage this financial uncertainty.

On the other hand, a carbon tax offers price certainty, but the resulting emissions reduction cannot be predetermined. By imposing a fixed cost on every unit of emissions, businesses know in advance how much they will have to pay per unit of emissions and can plan their investments in emission reduction technologies accordingly. Unlike an ETS, a carbon tax does not provide certainty about the total amount of emissions that will be produced (Figure 21). The actual emissions would depend on businesses' responses to the tax – how much they can and choose to reduce their emissions in response to the tax. This is why a carbon tax offers price certainty, but the resulting emissions reduction cannot be predetermined.

Finally, implementing a carbon tax can be a more straightforward process because it can be integrated into the current tax structure. This approach avoids the need for developing a new trading framework, making it relatively simple to put into effect.

An Emissions Trading System, in contrast, tends to offer greater flexibility. It allows for various mechanisms like offsets (where companies can pay for external projects that reduce emissions), banking (which lets companies save or 'bank' their unused allowances for future use), and limited borrowing (where entities can borrow a limited number of future allowances for current use). These options provide entities with more strategic choices concerning when and where to minimize their emissions.

The decision to adopt ETS or a carbon tax is influenced by a region's policy inclinations and specific characteristics. It's important to note that these two systems aren't incompatible: numerous jurisdictions use both ETS and carbon taxes in harmony, targeting different industries with each system (ICAP, 2021).

3.4.4 Carbon rebates and port charges incentives

Financial rewards can help lower pollution and encourage the use of eco-friendly ships and port technology. Many studies have looked at how these financial rewards work. They found that adjusting port fees can help make our oceans cleaner, which can also benefit society by improving the health of people living near ports. (Camargo-Díaz, 2022).

Port-based incentives refer to measures that offer rewards to ships that meet certain environmental or sustainability criteria when calling at a port. These incentives are designed to encourage shipping companies to adopt more sustainable practices, reduce their environmental impact, and improve the efficiency of their operations.

Examples of port-based incentives include:

- Reduced port fees or charges for ships that use low-emission fuels or have implemented energy-saving measures.
- Preferential berthing or priority access to port services for ships that meet certain environmental standards.
- Financial incentives, such as tax rebates or subsidies, for ships that adopt cleaner technologies or practices.
- Recognition or certification programs that provide ships with a formal acknowledgement or designation for their sustainability efforts.

Port-based incentives are typically offered by individual ports or groups of ports and may be tailored to address specific environmental challenges or priorities in a particular region. They are intended to complement broader policy measures, such as emissions regulations or carbon pricing schemes, by providing a tangible motive for shipping companies to invest in sustainable practices and technologies.

Differentiated port tariffs, which offer reduced fees for greener ships, are indeed the most common incentive. This can be attributed to the increasing environmental pressures ports face, alongside their commitments to climate change adaptation and mitigation. Various indices, labels, and certifications that monitor emission levels further facilitate the implementation of this strategy, as they provide transparency and standardization (Camargo-Díaz, 2022).

The primary goal of ecologically differentiated port fees is to charge lower rates for less polluting ships, which implies that the most "green" and clean boats receive a set or proportionate discount on the usual port price. Ports use a variety of discount and rebate billing structures, in accordance with the kind or size of the ship and its ecologically friendly technical performance.

Many ports provide green discounts and refunds ranging from 0.5% to 20% of port costs. The maximum rebate amounts vary from 3% to 80%. Rebates are normally levied on costs based on the size of the vessel or, in some situations, on the kind of vessel. (Piotrowicz, Kalinowski, Burchacz, Koba, & Kowalczyk, 2021)

Summing up, port-based incentives are key to fostering eco-friendly shipping practices and minimizing the ecological footprint of the maritime industry, especially around heavily populated areas. By offering rewards or reductions for those who prioritize sustainability, these incentives can establish a fairer competitive environment for shipping companies committed to environmental responsibility. Additionally, it can also enhance a port's competitiveness.

3.5 OTHER COUNTRIES' STRATEGIES / SCHEMES

There are numerous subnational carbon pricing plans in use on various industries, with UK's and California's ETS being the oldest. Still, the percentage of GHG emissions subject to national and subnational carbon pricing varies from less than 30% in some cases, to more than 70% in others such as Canada, Germany, Korea and Sweden, and the average price across the economy ranges from less than $5 to more than $100 per tonne. (Parry, Black, & Zhunussova, 2022)

3.5.1 UK

On the necessity of combating climate change Post-Brexit, the United Kingdom has established its own emissions trading scheme (UK ETS). The scheme mirrors its EU counterpart in many aspects but with the goal of reaching net-zero carbon emissions by 2050 – a more ambitious target compared to the EU's (Watson Farley & Williams, 2021) – including the domestic maritime sector, after the British government revised the Climate Change Act in 2019.

However, the expansion of the EU ETS to include maritime sectors, covering 50% of emissions from extra-EU voyages by large vessels, will significantly impact the UK due to the international nature of the shipping sector. This effect is heightened by the UK's concurrent proposal to extend the UK ETS to cover the domestic maritime sector. The UK aims to design a policy that prevents double charging of emissions. This approach will

include a review mechanism to ensure adaptability in the face of international measures that might influence a UK scheme. If such measures are adopted, the UK will be able to evaluate and redesign relevant aspects of the scheme that could be subject to double charging or to address identified loopholes. This approach allows for flexibility and ensures compliance with international norms while maintaining the scheme's effectiveness (UK - DfT, 2022).
The impacts of various obligations on international operators will be monitored and assessed as the industry adapts to this new regulatory landscape. The Climate Change Committee, an advisory body to the UK government, has suggested that implementing an emissions trading scheme is just one of the possible pathways to reduce emissions from shipping. They are also contemplating other strategies, such as introducing a carbon tax and promoting the use of zero-carbon fuels. This diversified approach reflects the complex and multifaceted challenge of achieving significant emissions reduction in the maritime sector (UK Department for Transport, 2022)

3.5.2 USA

To align the sector with the Paris Agreement's goals, the United States and Norway initiated the Green Shipping Challenge at COP27. This initiative urged governments, ports, and corporations to commit to propelling the green shipping transition.
The Challenge was launched during COP27's World Leaders Summit, under the guidance of Norwegian Prime Minister, Jonas Gahr Støre, and U.S. Special Presidential Envoy for Climate, John Kerry. Over 40 significant announcements about innovations for ships, the expansion of low- or zero-emission fuels, and policies promoting next-generation vessel adoption were made. As part of its commitment to combating the climate crisis, both domestically and internationally, the United States is spearheading the transition to zero-emission shipping. This includes the introduction of a $3 billion rebate and grant program under the Inflation Reduction Act for zero-emission port equipment or technology, along with technical assistance for electrification and emissions reduction planning.
In addition, more than $703 million was announced by the U.S. Department of Transportation to improve port facilities through the Maritime Administration’s Port Infrastructure Development Program. The funding will benefit various ports, enhancing

supply chain reliability through increased port capacity, efficiency, reduced emissions, and new workforce opportunities.

Internationally, the U.S. is collaborating with nations in the International Maritime Organization to set a goal of phasing out GHG emissions from international shipping no later than 2050. This initiative includes intermediate goals for 2030 and 2040, and an emphasis on a just transition that doesn't leave anyone behind.

New initiatives under the Green Shipping Challenge involve the establishment of U.S. Green Shipping Corridors in cooperation with South Korea, Canada, and the United Kingdom. These projects will explore the potential of creating green shipping corridors between significant cargo ports and host consultations with ports and stakeholders.

As part of the commitment to address the climate problem both domestically and internationally, the U.S., along with its partners, is committed to building on these initiatives to facilitate the transition to zero-emission maritime operations (US Department of state, 2022).

The United States does not have specific carbon pricing schemes directly targeting maritime emissions. It's important to note that the U.S. lacks a federal carbon pricing policy, with climate change mitigation strategies primarily driven by state-level initiatives, federal regulations, and voluntary actions by private companies.

It is also worth noting that certain regions or states in the U.S., such as California, have implemented broader cap-and-trade systems which include various sectors (California Air Resorces Board, 2023). While these programs do not directly target maritime emissions, they influence industries associated with shipping, such as port operations and electricity generation.

Launched in 2012, the California Cap-and-Trade Program regulates about 75% of the state's greenhouse gas emissions. It covers around 400 facilities across the power, industrial, transportation and buildings sectors. The program distributes allowances through auctions, free allocations and consignment, with proceeds from auctions reinvested into projects that further reduce emissions, thereby benefiting the economy, public health and environment. Notably, the program emphasizes on supporting disadvantaged communities (ICAP, 2023).

3.5.3 CHINA

China's National Emissions Trading Scheme was established in 2021 and is now the world's largest cap-and-trade system, covering more than 4 billion tonnes of CO_2 emissions, and accounting for over 40% of China's carbon emissions. The system initially regulates over 2,000 companies in the power sector that have annual emissions exceeding 26,000 tonnes of CO_2, including combined heat and power producers and captive power plants in other sectors.

The ETS is intensity-based, meaning emission caps are set relative to companies' outputs. Allowances are freely allocated using benchmarks based on historical emissions and industry standards, thus encouraging companies to reduce emissions while maintaining productivity.

The system also extends to China-flagged vessels, bringing the maritime sector into the scheme. As such, the China National ETS provides an example of how emissions trading can be effectively implemented at the national level, showing how market mechanisms can incentivize carbon reduction in a cost-effective way.

4 CARBON PRICING IMPACT

Carbon pricing as a strategy provides a clear market signal that incentivizes investment in low-carbon technologies and behavior changes. This mechanism not only encourages a shift towards cleaner and greener alternatives but also generates revenue that can be channeled towards research and development efforts for low-carbon alternatives or to offset the costs of emission reduction measures. It is important to gain an overview of such strategies' application in other industries as, drawing lessons from these experiences can provide valuable insights for the forthcoming introduction of carbon pricing in the shipping sector, enabling policymakers and stakeholders to design tailored and effective mechanisms for addressing the industry's carbon footprint.

Governments and regional policymakers worldwide have recognized the importance of carbon pricing as a policy instrument for mitigating the carbon footprint associated with prominent industries such as energy and power generation, manufacturing, industrial processes, agriculture and transportation. By introducing carbon pricing mechanisms, these policies seek to impose a financial cost on carbon emissions, thereby incentivizing these industries to adopt measures that minimize their environmental impact.

By 2022, sixty-eight carbon pricing plans were in place around the world, thirty-seven of which were explicitly taxing carbon and thirty-four were emissions-trading programs (World Bank, 2022). Over 23% of the world's GHG emissions were covered by the 68 carbon-pricing programs in 2022 and their earnings peaked at nearly $84 billion in 2021 (World Bank, 2022). Also, nearly all nations impose fuel excise taxes, which serve to adequately pricing carbon (OECD Publishing, 2022). Road fuel excise tax rates frequently exceed carbon tax rates and the cost of tradable permits. Unfortunately, their rates are not in line with the carbon content of fuels and frequently only apply to fuels used in the construction and road transportation industries (Forum & International Transport Forum, 2021).

The introduction of carbon pricing schemes has raised certain issues that need careful attention. A significant concern is the potential financial strain such schemes could place on low-income households and small businesses. These groups may end up shouldering a disproportionate share of the costs, particularly if they are already economically vulnerable.

At the same time, there are concerns regarding the effectiveness of carbon pricing in achieving climate change mitigation goals. If the price on carbon emissions is set too low, it may not serve as an effective deterrent to activities that result in emissions. In addition to failing to discourage carbon-intensive practices, a too-low price point may also fail to bridge the economic gap necessary for the adoption of greener technologies. In effect, it might not create the cost incentive required for industries and consumers to invest in environmentally friendly alternatives. Consequently, such a pricing scheme may fall short of significantly contributing to global climate objectives (ITF, 2022).

Additionally, reliance on carbon pricing alone may not fully address the varied and complex factors driving emissions. Climate change is propelled by a mixture of technological, economic, and behavioral elements, all of which require dedicated attention and action. As such, carbon pricing should be considered one component within a wider array of policies and measures designed to tackle these interconnected issues.

Hence, while carbon pricing remains a promising approach for combating climate change, careful attention must be given to the design and implementation of such schemes. Policymakers should consider a holistic, multifaceted approach that balances the need for climate action with the potential economic implications for vulnerable groups, and ensures it is part of a larger, integrated strategy to reduce emissions.

4.1 EFFECTIVENESS OVERVIEW

Very few research has been conducted to explore the post-implementation effects of carbon pricing. Thirty-seven studies that can be regarded as robust, in terms of isolating the amount of emission reductions owing to the carbon pricing policy, were found in Green's review analysis of former assessment of the effectiveness of carbon pricing policy (Green, 2021). There are additional impact studies that do not specifically examine the impact of carbon price; the emission reductions in these studies may have resulted from other causes. According to Green's overview study, carbon pricing has a relatively minor overall impact on emissions reduction, typically between 0% and 2% per year (Green, 2021).

Although the evidence is not entirely conclusive, carbon taxes seem to generate reductions slightly more effectively than emission trading systems. Over several years, carbon prices in European countries lowered emissions by up to 6.5%; yet, countries without a carbon tax reduced emissions quicker, indicating that other policies may have reduced emissions more than carbon taxes (Haites, 2018). According to a different study, emissions drop by 7.3% per each €10 rise in the cost of carbon (Sen & Vollebergh, 2018).

Employing all-encompassing policy packages and integrated strategies to promote the shift towards sustainability can lead to a decrease in immediate production expenses. Combining green public investments with carbon taxes can stimulate overall demand in the short run and alleviate constraints in energy supply.

Fears regarding the actual financial expenses associated with the shift towards sustainable energy have significantly contributed to delays in implementing policy changes over the years. Although the costs are often viewed as immediate and evident, the advantages are regarded as distant and uncertain. However, numerous pieces of evidence demonstrate that any short-term expenses will be far outweighed by the long-term benefits, including financial stability, improved health and output, of preventing climate change (IMF, 2020).

4.2 WHO PAYS THE CARBON PRICE?

The "polluter pays" principle is a strategy used to deal with the issue of externalities. Externalities are the side effects of a financial transaction or a broader economic activity that affect third parties who aren't directly involved in the transaction or the community.

The main concern here is determining who should be responsible for the pollution: the business generating the pollution and profiting from it; the consumers who enjoy the company's products; the nearby residents who might be negatively affected; or everyone in society. If there is no intervention, those living nearby (downstream neighbors) are likely to suffer the consequences.

The "polluter pays" principle suggests that the company causing the pollution should be held responsible for its costs. This cost might eventually be transferred to the consumers, as the expense of managing the pollution becomes part of the product's price. This is a way to internalize the cost that was previously external, affecting those not involved in the transaction (Hillary Aidun, 2021).

Carbon pricing in the shipping industry is directly linked to the “polluter pays” principle. In this context, the polluters are the shipping companies, and the externality is the carbon emissions released into the atmosphere during their operations. These emissions contribute to global warming and have widespread impacts on society, yet they are not reflected in the cost of shipping goods.

MBMs seek to internalize these external costs by charging companies for their greenhouse gas emissions. This provides an economic incentive for these companies to reduce their carbon footprint, as the more they emit, the more they would have to pay. For example, they might invest in cleaner technologies or more efficient shipping methods to reduce their emissions and thus their costs.

Moreover, like the principle's application in other sectors, the cost of carbon pricing in the shipping industry might eventually be passed on to consumers. As the price of shipping increases due to carbon costs, the cost of goods transported by ships might also increase. In this way, the environmental cost of shipping is more accurately reflected in the price of the goods, making consumers who drive the demand for these goods share in the cost of pollution.

4.3 CARBON PRICE LEVELS

The effectiveness of a carbon pricing instrument in meeting its objectives heavily relies on accurately determining the carbon price. Various methodologies to identify this “appropriate” price exist, depending on the ultimate goal of the instrument (Baresic, 2022) (World Bank, 2022) (IMO, 2020):

- **Reflecting the Social Cost of Carbon (SCC):** This approach aligns the carbon price with the societal cost of each additional tonne of CO_2 emissions. However, SCC estimates carry substantial uncertainties.
- **Target-consistent Carbon Prices:** Here, the necessary carbon price is inferred from a given emission reduction or temperature target. While this method still involves uncertainties, it is generally less uncertain than SCC.
- **Revenue-raising Carbon Prices:** If the goal is to generate a specific amount of revenue, the required carbon price can be calculated to realize this target.

- **Replicating Carbon Prices from Existing Schemes:** To increase the political acceptance of a carbon pricing instrument, it could be beneficial to emulate the price levels used in existing schemes. However, these prices are usually below the levels required for Paris Agreement compliance.

To fulfill IMO's Initial GHG Strategy's ambition levels, according to the mentioned studies, an average carbon price of $173 per tonne of CO_2 is necessary to achieve a 50% reduction in shipping GHG emissions by 2050. For full decarbonization by 2050, the price should be slightly higher, around $191 per tonne of CO_2. Both scenarios anticipate the introduction of carbon pricing in the mid-2020s. For a full switch to zero-emission fuels, the carbon price would need to increase significantly by 2030.

4.4 A NEW REVENUE STREAM

In 2021, carbon pricing revenues saw a significant surge, primarily due to an increase in carbon prices, with Emissions Trading Systems surpassing carbon taxes in generating revenue for the first time. The total global carbon pricing revenue for the year was approximately $84 billion, a hike of over $31 billion compared to the prior year (World Bank, 2022). This growth was predominantly driven by higher carbon prices, particularly within the EU ETS, which accounted for about 41% of all carbon pricing revenue. Furthermore, the New Zealand ETS, which started auctioning allowances, and the California Cap-and-Trade Program also played key roles in the rise of carbon revenue.

Two newly operational ETSs in 2021, UK ETS and Germany ETS, contributed over 16% of the total carbon pricing revenue. On the contrary, Chinese national ETS, which is the largest in operation based on emission coverage, did not generate any revenue as it allocated all allowances for free (S&P Global Commodity Insights, 2023).

Historically, carbon taxes have yielded more revenue than Emission Trading Schemes, however, the difference has lessened in recent years. In 2021, ETSs were responsible for over two-thirds of the total revenue, as shown in Figure 22 (World Bank, 2022). This is predominantly due to the faster rise in ETS prices compared to fixed-price instruments. Another contributing factor is the growing proportion of allowances being auctioned off, as opposed to being freely allocated.

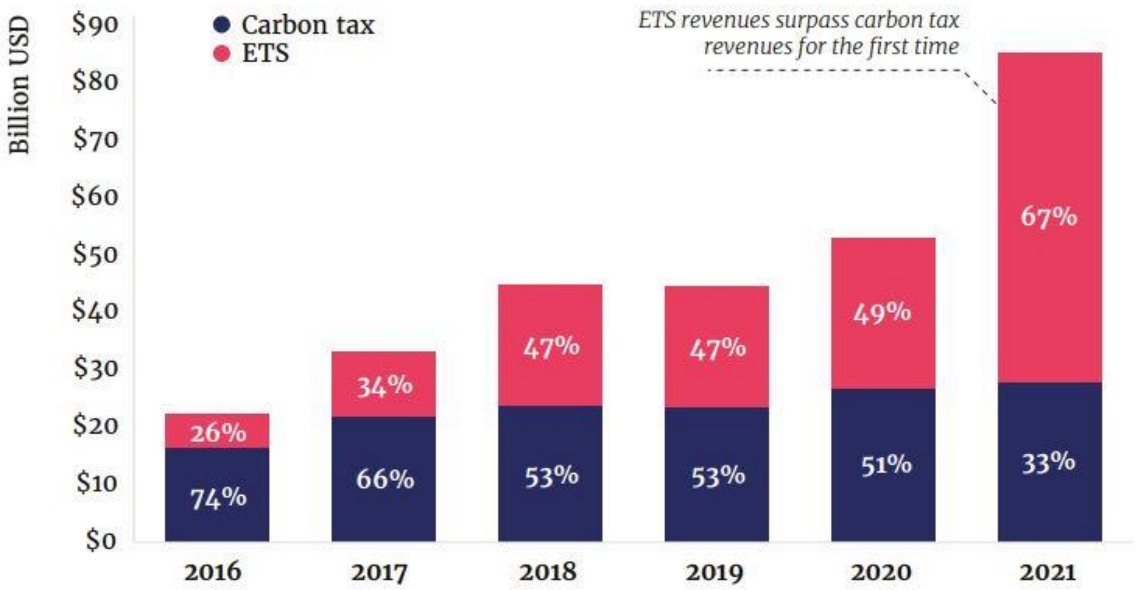

Figure 22

For the first time ever, revenues generated by ETSs surpassed revenues generated by carbon taxes (World Bank, 2022)

It is a fact that not all market-based measures are of equal merit. They indeed instigate financial stimuli through price signals, encouraging industry-wide modifications in practices to expedite the transition towards low and zero-carbon shipping. Yet, certain measures, such as carbon levies or cap-and-trade systems devoid of free emissions allowance allocations, can garner significant revenues (Baresic, 2022) (IMO, 2020) (The World Bank , 2022). This not only facilitates additional climate and development initiatives, but also establishes a unique feature, unparalleled by other policies. In the shipping sector alone, these carbon revenues could potentially accumulate an estimated $1 trillion to $3.7 trillion by 2050, which equates to an annual $40-$60 billion. This prospect necessitates an understanding of the types of endeavors that could be financed with the advent of carbon revenues. Additionally, identifying the most appropriate recipients of these funds from this novel revenue stream becomes crucial.

The *World Bank report* (The World Bank , 2022) elucidates several possible uses for the revenues derived from carbon pricing. Foremost on the priority agenda is the decarbonization of the shipping industry. This involves championing the advancement of zero-carbon vessels and fuels, establishing production and distribution networks for environmentally friendly bunker fuels, and enhancing port infrastructure to support these new technologies, among others. A portion of these funds could also be directed towards a more extensive upgrade of the maritime infrastructure, such as fortifying the overall resilience of maritime ports. These ports, often struggling by climate-induced severe weather events, congestion, inadequate digitalization or a shortage of skilled labor, would benefit from this intervention.

Considering the significant revenues that could be generated through carbon pricing and their effectiveness in reducing GHG emissions from ships, there are further opportunities to allocate some of these resources beyond the maritime sector. For example, redirecting a portion of the carbon revenues to facilitate the production of greener electricity would be an effective strategy to boost the broader energy transition, create jobs, and ameliorate air quality. This would constitute a clear win-win situation, as it would also benefit the shipping industry in the long term, whose new fuels will heavily depend on the extensive availability of renewable power worldwide.

As the battle against climate change escalates, carbon pricing is poised to become a key component of the development discourse. This relevance extends beyond the shipping industry to any sector where technology alone cannot immediately bring about the radical GHG emissions reductions required to keep global climate goals attainable. Although each industry has unique characteristics, the findings from this report offer some valuable insights for “hard-to-abate” sectors (The World Bank , 2022). These pertain to designing effective carbon pricing mechanisms, maximizing the benefits from these new revenues, and ensuring that the transition is equitable, leaving no country at a disadvantage.

5 CONCLUSIONS

The maritime industry, a sector historically challenging to decarbonize, is currently navigating a complex transitional period. The investigation conducted in this study on potential applications of carbon pricing options within the shipping industry has uncovered numerous opportunities and challenges related to carbon pricing mechanisms. Implementing these pricing systems could serve as a powerful tool to drive sustainability within the sector by monetizing carbon emissions, thereby incentivizing the shift away from carbon-intensive operations.

The International Maritime Organization's comprehensive fourth study on greenhouse gas emissions emphasizes the pivotal role of alternative fuels in achieving the climate targets set for 2050. The expansion of IMO's initial strategy reflects a clear indication of future expectations. The imminent implementation of the European Union's Emissions Trading Scheme and the forthcoming FuelEU for shipping further exemplify the industry's shift based on lessons learned from the implementation of carbon pricing in other sectors. In addition, the focus on lifecycle emissions and the emphasis on addressing well-to-wake emissions throughout the supply chain, underscore a holistic approach and a global commitment to the goals outlined in the Paris Agreement.

Notably, carbon pricing mechanisms essentially serve as economic tools that generate revenue. Shipping alone has the potential to accumulate significant funds, estimated at $1 trillion to $3.7 trillion by 2050, which can be directed towards various initiatives aimed at achieving sustainable practices and deep decarbonization for shipping.

Nevertheless, the successful implementation and effectiveness of these strategies hinge on various factors. These include ensuring equitable outcomes, considering economic realities, establishing robust governance, fostering international collaboration, and developing a comprehensive legal framework to ensure a level playing field across the sector. Another crucial factor involves aligning the incentives of all stakeholders in the maritime industry. Aligning incentives can drive collective action, harmonizing efforts towards sustainable transformations and ensuring all parties share the burden and benefits of decarbonization equally. The industry landscape is evolving rapidly, and all players within the maritime sphere must adapt accordingly to remain competitive. This adaptation requires a mindset shift towards more sustainable practices across the supply chain, a commitment to equity, operational flexibility, and proactive investments in innovative technologies. In the dawn of this new era, early adopters may reap substantial rewards.

While the effectiveness of market-based mechanisms for deep decarbonization of the shipping industry is yet to be fully determined, the direction of change has undoubtedly been signaled. Therefore, the industry and its stakeholders must now face this challenge head-on and navigate the path towards a more sustainable maritime future.

REFERENCES

Ågren, C. (June 2014). SCR can cut ship NOx emissions. *Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction*.

Baresic, D. R. (2022). Closing the Gapp: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping. (UMAS, Ed.) London, UK. Retrieved from https://www.globalmaritimeforum.org/content/2021/12/Closing-the-Gap_Getting-to-Zero-Coalition-report.pdf

BIMCO. (2023). *The wrong speed for all the wrong reasons*. Retrieved from www.bimco.org: https://www.bimco.org/insights-and-information/general-information/20230522-sail-fast-then-wait

Bureau Veritas. (2023). *FUELEU MARITIME* . Retrieved from marine-offshore.bureauveritas.com: https://marine-offshore.bureauveritas.com/sustainability/fit-for-55/fueleu-maritime

Bureau Veritas. (2023). *WHAT WELL-TO-WAKE DECARBONIZATION MEANS FOR SHIPOWNERS*. Retrieved from https://marine-offshore.bureauveritas.com/: https://marine-offshore.bureauveritas.com/what-well-wake-decarbonization-means-shipowners#:~:text=What%20does%20well%2Dto%2Dwake,and%20all%20emissions%20produced%20therein.

California Air Resorces Board. (2023). *Cap-and-Trade Program*. Retrieved from ww2.arb.ca.gov: https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/about

Camargo-Díaz, C. P. (2022). A Review of Economic Incentives to Promote Decarbonization.

ClassNK. (2023, May). *Adoption of EU-ETS for shipping sector and amendments to EU-MRV.* Retrieved from www.classnk.or.jp: https://www.classnk.or.jp/hp/pdf/tech_info/tech_img/T1299e.pdf

ClassNK. (2023). *FAQs on the EU-ETS for Shipping.* Retrieved from www.classnk.com: https://www.classnk.com/hp/pdf/authentication/eumrv/EUETS_faq_e.pdf

Climate Analytics and NewClimate Institute. (2021, 7). *Climate Action Tracker*. Retrieved from Climate Analytics and NewClimate Institute: https://climateactiontracker.org/sectors/shipping/

CLIMEON. (2023). *EU ETS Shipping Carbon Tax Announced*. Retrieved from climeon.com: https://climeon.com/eu-ets-shipping-carbon-tax-announced/

Consulting, F. (2019). Low carbon pathways until 2050.

Cullinane, K., & Yang, J. (2022). Evaluating the Costs of Decarbonizing the Shipping Industry:. *Journal of marine science engineering*.

DNV. (2019). *EU ETS – Emissions Trading System.* Retrieved from https://www.dnv.com/maritime/insights/topics/eu-emissions-trading-system/index.html?gclid=CjwKCAiA9NGfBhBvEiwAq5vSy-c6F3rg8M1mJgsz0YhnFnfj2T3jUcXBk0uwBHH6EhPJcY7p0izcJxoCpCUQAvD_BwE

DNV. (2022). *Maritime Forecast to 2050 - Energy Transition Outlook 2022.* DNV. Retrieved from https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html

EMSA. (2023). *Anti-fouling*. Retrieved from https://www.emsa.europa.eu/protecting-the-marine-environment/anti-fouling.html

EMSA. (2023). *Thetis*. Retrieved from https://portal.emsa.europa.eu/: https://portal.emsa.europa.eu/web/thetis

EPA. (2023). *EU Emissions Trading System*. Retrieved from epa.ie: https://www.epa.ie/our-services/licensing/climate-change/eu-emissions-trading-system-/

EU Taxation and Customs Union. (2023). *Carbon Border Adjustment Mechanism*. Retrieved from taxation-customs.ec.europa.eu: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

European Commission. (2022). *FuelEU Maritime.* Retrieved from european-dredging.eu: https://european-dredging.eu/pdf/01-DG_MOVE_on_FuelEU_Maritime.pdf

European Commission. (2023). *Reducing emissions from the shipping sector.* Retrieved from climate.ec.europa.eu: https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en

European Council. (2023). *FuelEU Maritime initiative: Provisional agreement to decarbonise the maritime sector*. Retrieved from www.consilium.europa.eu: https://www.consilium.europa.eu/en/press/press-releases/2023/03/23/fueleu-maritime-initiative-provisional-agreement-to-decarbonise-the-maritime-sector/

European Council. (2023). *Infographic - Fit for 55: increasing the uptake of greener fuels in the aviation and maritime sectors*. Retrieved from www.consilium.europa.eu: https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu/

European Environment Agency. (2023). *What is particulate matter and what are its effects on human health?* Retrieved from eea.europa.eu: https://www.eea.europa.eu/help/faq/what-is-particulate-matter-and

Forum, I. T., & International Transport Forum. (2021). Carbon Pricing in Shipping.

GARD. (2022). *The EU Emission Trading System - are you ready?* Retrieved from https://gard.no/: https://gard.no/web/articles?documentId=34594894

Green, J. (2021). Does carbon pricing reduce emissions? A review of ex-post analyses. *Environmental Research Letters, 16*(4).

Haites, E. (2018). Carbon taxes and greenhouse gas emissions trading systems: What have we learned? *Climate Policy*,.

Helmi, T. (2021). *Decarbonizing Shipping: All Hands on Deck.* Retrieved from https://www.deloitte.com/global/en/Industries/energy/perspectives/decarbonizing-shipping.html

HEMPEL. (2021). *Get ready for CII now: Paint your way.* Retrieved from https://www.hempel.com/markets/marine/cii?utm_source=google&utm_medium=cpc&utm_campaign=paintyourway&utm_content=search&gclid=CjwKCAiAxvGfBhB-

EiwAMPakqhxapn-5Juo2dePMkZvu9Hv2qgPAsPduUxHc95r2ROyEeYXyiCrpGhoCPokQAvD_BwE

Hessevik, A. (2022). *Green shipping networks as drivers of decarbonization in offshore shipping companies*. Retrieved from Science Direct: https://www.sciencedirect.com/science/article/pii/S2666822X22000041#sec0001

Hillary Aidun, D. J. (2021). *Principles of International Law and the Adoption of a Market-Based Mechanism for Greenhouse Gas Emissions from Shipping.* Columbia Law School. Retrieved from https://scholarship.law.columbia.edu/faculty_scholarship/2749?utm_source=scholarship.law.columbia.edu%2Ffaculty_scholarship%2F2749&utm_medium=PDF&utm_campaign=PDFCoverPages

Holman Fenwick Willan LLP. (2022). *EU EMISSIONS TRADING SYSTEM: CURRENT STATUS AND KEY ISSUES*. Retrieved from www.hfw.com: https://www.hfw.com/EU-Emissions-Trading-System-Current-status-and-key-issues-July-2022

Howard, G. (2022, February 08). *Decarbonizing shipping could be a $6trn effort.* Retrieved from https://www.seatrade-maritime.com/regulation/decarbonizing-shipping-could-be-6trn-effort

Ian Parry. (2021, September). *Five Things To Know About Carbon Pricing.* Retrieved from https://www.imf.org/en/Publications/fandd/issues/2021/09/five-things-to-know-about-carbon-pricing-parry

ICAP. (2021). *EMISSIONS TRADING AND CARBON TAX: TWO INSTRUMENTS, ONE GOAL.* Retrieved from https://icapcarbonaction.com/: https://icapcarbonaction.com/system/files/document/20_icap_briefs-8_updated-2021.pdf

ICAP. (2023). *Emissions Trading Worldwide: Status Report 2023.* Berlin. Retrieved from https://icapcarbonaction.com/system/files/document/ICAP%20Emissions%20Trading%20Worldwide%202023%20Status%20Report_0.pdf

ICAP. (2023). *ICAP Emissions Trading Worldwide 2023 Status Report.* Berlin. Retrieved from https://icapcarbonaction.com/: https://icapcarbonaction.com/system/files/document/ICAP%20Emissions%20Trading%20Worldwide%202023%20Status%20Report_0.pdf

ICAP. (2023). *USA - California Cap-and-Trade Program.* International Carbon Action Partnership. Retrieved from https://icapcarbonaction.com/system/files/ets_pdfs/icap-etsmap-factsheet-45.pdf

ICS. (2022). *Initial impact assessment on States of a carbon levy for international shipping.* Retrieved from https://www.ics-shipping.org/wp-content/uploads/2022/04/ISWG-GHG-12-3-8-Initial-impact-assessment-on-States-of-a-carbon-levy-for-international-shipping-ICS.pdf

ICS. (2023). *FURTHER CONSIDERATION AND FINALIZATION OF THE ASSESSMENT AND SELECTION OF MEASURE(S) TO FURTHER DEVELOP IN THE CONTEXT OF PHASE II OF THE WORK PLAN FOR THE DEVELOPMENT OF MID- AND LONG-TERM MEASURES.* IMO. Retrieved from https://www.ics-shipping.org/wp-content/uploads/2023/02/ISWG-GHG-14-3-Further-information-about-revised-IMSFR-proposal-and-possible-draft-amendments-toMARPOL-A...-ICS.pdf

ICS. (2023). *Shipping and World Trade: World Seaborne Trade*. Retrieved from https://www.ics-shipping.org/shipping-fact/shipping-and-world-trade-world-seaborne-trade/

ICS. (2023). *The International Chamber of Shipping reaffirms commitment to 2050 net zero*. Retrieved from www.ics-shipping.org: https://www.ics-shipping.org/press-release/the-international-chamber-of-shipping-reaffirms-commitment-to-2050-net-zero/

IMF. (2020). *MITIGATING CLIMATE CHANGE—GROWTH- AND DISTRIBUTION-FRIENDLY STRATEGIES.* Retrieved from https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020

IMO. (2018). *Pollution Prevention.* Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx

IMO . (2019). *IMO Data Collection System (DCS)*. Retrieved from www.imo.org: https://www.imo.org/en/ourwork/environment/pages/data-collection-system.aspx

IMO. (2019). *IMO 2020 - cleaner shipping for cleaner air*. Retrieved from www.imo.org: https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx

IMO. (2019). *Marine Environment Protection Committee (MEPC)*. Retrieved from imo.org: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-default.aspx#:~:text=The%20Marine%20Environment%20Protection%20Committee,environmental%20issues%20under%20IMO's%20remit.

IMO. (2020). *Environment*. Retrieved from https://www.imo.org/en/OurWork/Environment/Pages/Default.aspx

IMO. (2020). *Fourth GHG Study.* Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf

IMO. (2020). *Fourth Greenhouse Gas Study 2020*. Retrieved from imo.org: https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

IMO. (2021). *Market-Based Measures.* Retrieved from IMO: https://www.imo.org/en/OurWork/Environment/Pages/Market-Based-Measures.aspx

IMO. (2022). *Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines)*. Retrieved from www.imo.org/en: https://www.imo.org/en/OurWork/Environment/Pages/Lifecycle-GHG---carbon-intensity-guidelines.aspx

IMO. (2023). *Anti-fouling systems*. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/FOULING2003.pdf

Intergovernmental Panel on Climate Change. (2022, February 28). *Climate change: a threat to human wellbeing and health of the planet.* Retrieved from https://www.ipcc.ch/report/ar6/wg2/resources/press/press-release/

Isabelle Rojon, N.-J. L. (2021). The impacts of carbon pricing on maritime transport costs and their implications for developing economies. *Marine Policy*,. doi:https://doi.org/10.1016/j.marpol.2021.104653.

ITF. (2022). *Carbon Pricing in Shipping.* International Transport Forum Policy Papers. Paris: OECD Publishing. Retrieved from International Transport Forum Policy Papers,: https://www.itf-oecd.org/sites/default/files/docs/carbon-pricing-shipping.pdf

Joshi, A. (2020). Review of vehicle engine efficiency and emissions. *SAE Technical Paper, 01*(0352).

Korean Register of Shipping – RnD Division. (2020). Forecasting the Alternative Marine Fuel Ammonia. Retrieved from Korean Register of Shipping– RnD Division, “Forecasting the Alternative Marine Fuel Ammonia”, 2020

Lind, M., & Lehmacher, W. (2022). *Decarbonizing the maritime sector: Mobilizing coordinated action in the industry using an ecosystems approach.* Retrieved from https://unctad.org/news/decarbonizing-maritime-sector-mobilizing-coordinated-action-industry-using-ecosystems-approach#:~:text=The%20commonality%20is%20decarbonizing%20shipping,redress%20today's%20increasingly%20fragmented%20world.

Lloyd's Register - LR. (2023). *EU carbon pricing brings new pressures – and new plays – to maritime*. Retrieved from www.lr.org: https://www.lr.org/en/knowledge/technical-articles/eu-carbon-pricing-brings-new-pressures-and-new-plays-to-maritime/

Mærsk Mc-Kinney Møller Center. (2022). *The Role of Onboard Carbon Capture in Maritime Decarbonization*. Retrieved from https://www.zerocarbonshipping.com/: https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf

MAN Energy solutions. (2017). *Emissions Control for the maritime Industry.* Retrieved from https://www.man-es.com/marine/strategic-expertise/emissions-control?utm_medium=sea&utm_source=google&utm_campaign=always_sea_2020_man_generic_marine_solutions_bmm&utm_term=sel-sesm&gclid=Cj0KCQiAh4j-BRCsARIsAGeV12AyDpCPLDRKDxj9hQ3d1JALpzwwFYt-5H6RSibgJ7o7

Marine Insight. (2021, May 31). *4 Types of Anti-fouling Systems Used on Board Ships to Prevent Marine Growth.* Retrieved from https://www.marineinsight.com/tech/4-types-of-anti-fouling-systems-used-on-board-ships-to-prevent-marine-growth/

Maritim Africa. (2022). *Energy Efficiency White Paper, EEDI/EEXI overview, analysis and impact.*

Motorship Insight for marine technology. (2018). Reducing NOx emissions from Ship exhaust.

Mousiopoulos N., N. L. (2015). *Protection Technique Environment - Principles of sustainability*. Kallipos.

NABU. (2023). *Ammonia as Marine Fuel*. Retrieved from en.nabu.de: https://en.nabu.de/topics/traffic/30212.html

National Grid. (2023, Feb). *What is carbon capture and storage?* Retrieved from https://www.nationalgrid.com/: https://www.nationalgrid.com/stories/energy-explained/what-is-ccs-how-does-it-work#:~:text=CCS%20involves%20the%20capture%20of,deep%20underground%20in%20geological%20formations.

Norton Rose Fulbright . (2023, April). *Shipping and EU ETS: The changing landscape*. Retrieved from www.nortonrosefulbright.com: https://www.nortonrosefulbright.com/en/knowledge/publications/31c5c021/shipping-and-eu-ets#:~:text=Penalties%20for%20non%2Dcompliance%20with,been%20surrendered%2C%20will%20be%20incurred.

O'Dwyer, R. (2023). *Research suggests up to 7.3% fuel savings from voyage optimisation*. Retrieved from smartmaritimenetwork.com/: https://smartmaritimenetwork.com/2023/02/14/research-suggests-up-to-7-3-fuel-savings-from-voyage-optimisation/

OECD Publishing. (2022). *Pricing Greenhouse Gas Emissions; Turning Climate Targets into Climate Action.* Paris: OECD Publishing.

OGCI and Concawe. (2022). *Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050.* Retrieved from https://www.concawe.eu/wp-content/uploads/Technological-Operational-and-Energy-Pathways-for-Maritime-Transport-to-Reduce-Emissions-Towards-2050.pdf

Päivi T. Aakko-Saksa, K. L.-P. (2023). Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options,. *Science Direct*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360128522000624

Parry, I., Black, S., & Zhunussova, K. (2022). Carbon Taxes or Emissions Trading Systems? Instrument Choice and Design. *IMF STAFF CLIMATE NOTE*. Retrieved from https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/07/14/Carbon-Taxes-or-Emissions-Trading-Systems-Instrument-Choice-and-Design-519101

Piotrowicz, J., Kalinowski, M., Burchacz, M., Koba, R., & Kowalczyk, U. (2021). *Port dues strategies and incentives for cruise line companies for using green port feature.* Retrieved from http://www.greencruiseport.eu/files/public/download/studies/Port%20Dues%20Strategies%20and%20Incentives%20for%20Cruise%20Lines_30.06.2018_Gdansk.pdf

Psaraftis, H. (2012). Market-based measures for greenhouse gas emissions from ships: a review. *WMU Journal of Maritime Affairs*, 211–232. doi:https://doi.org/10.1007/s13437-012-0030-5

Psaraftis, H. Z. (2021). Impact assessment of a mandatory operational goal-based short-term measure to reduce GHG emissions from ships: the LDC/SIDS case study. *Int Environ Agreements*, 445–467. doi:https://doi.org/10.1007/s10784-020-09523-2

Psarautis, C. (2007). *Marine Pollution: Prevention & Suppression.* Athens: Laboratory for Maritime Transport.

S&P Global Commodity Insights. (2023). *China's national ETS update: Free allowances tightened but overall cost increase still limited*. Retrieved from www.spglobal.com: https://www.spglobal.com/commodityinsights/en/ci/research-analysis/chinas-national-ets-update-free-allowances-tightened.html

Sen, S., & Vollebergh, H. (2018). The effectiveness of taxing the carbon content of energy consumption. *Journal of Environmental Economics and Management, 92*, 74-99.

Stefan Gössling, C. M.-H. (2021). A global review of marine air pollution policies, their scope and effectiveness. *https://www.sciencedirect.com/*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0964569121003070

The Hong Kong Polytechnic University. (2013). *Product Carbon Footprint*. Retrieved from www.polyu.edu.hk: https://www.polyu.edu.hk/ise/ecodesign/product_carbon_footprint.html

The World Bank . (2022). *Carbon Revenues from International Shipping Technical Brief.* Washington DC: International Bank for Reconstruction and Development / The World Bank . Retrieved from https://openknowledge.worldbank.org/server/api/core/bitstreams/b2756433-6951-52ba-bfc5-94e22e57795b/content

Tvinnereim, E., & Mehling, M. (2018). Carbon pricing and deep decarbonization. *Energy policy, 121*, 185-189. Retrieved from https://pdf.sciencedirectassets.com/271097/1-s2.0-S0301421518X00081/1-s2.0-S0301421518304063/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEBMaCXVzLWVhc3QtMSJGMEQCIFSfzPnGclq6Fb58bJ4HkNe2GB2p0izjDwZgDGMxQ9i0AiAB%2FWlCIffWjnHilY29jM0HvDUPvTz6R72eWvAINzug6i

UK - DfT. (2022). *UK Domestic Maritime Decarbonization - Consultation: Plotting the Course to Zero.* London: UK - Department for Transport. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092399/uk-domestic-maritime-decarbonization-consultation-plotting-the-course-to-zero.pdf

UK Department for Transport. (2022). UK Domestic Maritime Decarbonization Consultation: Plotting the Course to Zero. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092399/uk-domestic-maritime-decarbonization-consultation-plotting-the-course-to-zero.pdf

UNCTAD. (2022). *Decarbonizing the maritime sector: Mobilizing coordinated action in the industry using an ecosystems approach*. Retrieved from https://unctad.org/: https://unctad.org/news/decarbonizing-maritime-sector-mobilizing-coordinated-action-industry-using-ecosystems-approach

UNFCCC . (2022). *A Guide to UN Market-based Mechanisms*. Retrieved from https://unfccc.int/blog/a-guide-to-un-market-based-mechanisms#:~:text=The%20Kyoto%20Protocol%20introduced%20three,and%20Emissions%20Trading%20(ET).

UNFCCC. (2018, 4 18). *World Nations Agree to At Least Halve Shipping Emissions by 2050*. Retrieved from United Nations Climate Change: https://unfccc.int/news/world-nations-agree-to-at-least-halve-shipping-emissions-by-2050

United Nations. (2022). *Marking the Kyoto Protocol's 25th anniversary*. Retrieved from un.org: https://www.un.org/en/climatechange/marking-kyoto-protocol%E2%80%99s-25th-anniversary

US Department of state. (2022). U.S. Announcements Under the Green Shipping Challenge at COP27. Retrieved from https://www.state.gov/u-s-announcements-under-the-green-shipping-challenge-at-cop27/

Valentin, L. (2022, March 14). *Different Ways to Reduce CO2 Emissions from Sea Freight.* Retrieved from https://sinay.ai/en/different-ways-to-reduce-co2-emissions-from-sea-freight/

Verifavia Shipping. (2023). *EU ETS for Maritime Transport*. Retrieved from www.verifavia-shipping.com: https://www.verifavia-shipping.com/shipping-carbon-emissions-verification/news-eu-ets-for-maritime-transport-675.php

Vogt-Schilb, A., G., M., & Hallegatte, S. (2018). When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment. *", Journal of Environmental Economics and Management, 88*, 210-233.

Wartsila. (2020, 03 25). *Wartsila-advances-future-fuel-capabilities-with-first-ammonia-tests.* Retrieved from https://www.wartsila.com/media/news/25-03-2020-wartsila-advances-future-fuel-capabilities-with-first-ammonia-tests-2670619

Watson Farley & Williams. (2021). A GREENER VOYAGE: NAVIGATING EMISSIONS TRADING SCHEMES FOR THE MARITIME SECTOR. London. Retrieved from https://www.wfw.com/articles/a-greener-voyage-navigating-emissions-trading-schemes-for-the-maritime-sector/

Wimmer, A. e. (2005). H2-direct injection–a highly promising combustion concept. . *SAE Technical Paper, 01*(0108).

World Bank. (2022). *State and Trends of Carbon Pricing 2022.* Retrieved November 2022, from https://openknowledge.worldbank.org/handle/10986/ 37455

World Port Sustainability Program. (2023). *On-shore power supply.* Retrieved from https://sustainableworldports.org/ops/

Yigit Kemal Demirel, M. K. (2013). *On the importance of antifouling coatings regarding ship resistance and powering.* Retrieved from Low Carbon Shipping Conference: https://strathprints.strath.ac.uk/47159/1/Demirel_et_al.pdf

Zachariadis, P. (2017, December 11). Marine environmental mechanisms.

Zis, T. (2018). Prospects of cold ironing as an emissions reduction option. *Transportation Research Part A Policy and Practice*.