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Green Transformation in Maritime Industry: The Role and Impact of Regulations

Denizcilik Sektöründe Yeşil Dönüşüm: Düzenlemelerin Rolü ve Etkisi

Türk Denizcilik ve Deniz Bilimleri Dergisi Cilt: XX Sayı: XX (202X) XX-XX

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ABSTRACT

As concerns over climate change and environmental sustainability continue to grow, the shipping industry faces increasing pressure to reduce its carbon footprint and adopt greener practices. In alignment with the United Nations Sustainable Development Goals (SDGs)—particularly SDG13 (Climate Action), SDG7 (Affordable and Clean Energy), and SDG9 (Industry, Innovation, and Infrastructure), this study aims to review the role and impact of green shipping regulations on the maritime industry, focusing on their effects on operational efficiency, financial structures, and technological innovation. By examining both target-based (e.g., Energy Efficiency Design Index, Carbon Intensity Indicator) and market-based (e.g., EU Emissions Trading System) regulatory measures, the study evaluates how these policies shape industrial productivity and competitiveness. It also highlights the challenges and opportunities stakeholders encounter while adapting to these regulations. The review provides critical insights for ship operators, policymakers, and researchers in developing effective strategies for a sustainable maritime industry.

Keywords: Maritime Sustainability, Decarbonization Efforts, Maritime Trade

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ÖZET

İklim değişikliği ve çevresel sürdürülebilirlik konusundaki endişeler artmaya devam ederken, denizcilik sektörü karbon ayak izini azaltma ve daha çevreci uygulamaları benimseme konusunda artan bir baskıyla karşı karşıya bulunmaktadır. Bu çalışma, Birleşmiş Milletler Sürdürülebilir Kalkınma Amaçları (SDG) -özellikle SDG13 (İklim Eylemi), SDG7 (Erişilebilir ve Temiz Enerji) ve SDG9 (Sanayi, Yenilikçilik ve Altyapı) ile uyumlu olarak, yeşil denizcilik düzenlemelerinin denizcilik sektörü üzerindeki rolünü ve etkisini, operasyonel verimlilik, finansal yapılar ve teknolojik yenilikçilik üzerindeki etkilerine odaklanarak incelemeyi amaçlamaktadır. Çalışma, hem hedef bazlı (örn. Enerji Verimliliği Tasarım Endeksi, Karbon Yoğunluğu Göstergesi) hem de piyasa bazlı (örn. AB Emisyon Ticaret Sistemi) düzenleyici tedbirleri inceleyerek, bu politikaların sektörel verimliliği ve rekabet gücünü nasıl şekillendirdiğini değerlendirmektedir. Ayrıca, paydaşların bu düzenlemelere uyum sağlarken karşılaştıkları zorlukları ve fırsatlar vurgulanmaktadır. Bu inceleme, sürdürülebilir bir denizcilik sektörü için etkili stratejiler geliştirmede gemi işletmecileri, politika yapıcılar ve araştırmacılar için kritik bilgiler sağlamaktadır.

Anahtar sözcükler: Denizcilikte Sürdürülebilirlik, Karbonsuzlaşma Çabaları, Deniz Ticareti

1. INTRODUCTION

Maritime transportation, the leading choice for intercontinental trade, facilitates the transport of diverse commodities efficiently while reducing logistics costs through economies of scale (Tran and Haasis, 2015). Maritime transportation is vital for international trade. Initially powered by oars or wind, ships transitioned to coal and later petroleum-based fuels, especially in the 19th century. Over the past 40 years, maritime trade has grown by 250%, driven by containerization and globalization, matching global GDP growth while outpacing energy consumption (170%) and population growth (90%) (Bouman *et al.*, 2017). However, since 2020, the industry has been undergoing significant transformation due to the enforcement of green maritime regulations (Balcombe *et al.*, 2019).

The global imperative to combat climate change has led to a significant shift towards green practices in industries worldwide. As countries strive to meet ambitious emission reduction targets in international agreements such as the Paris Agreement, regulatory authorities aiming to reduce greenhouse gas emissions are adapting and evolving rapidly. As a vital component of global trade, the maritime industry finds itself at the forefront of these regulatory changes. Because ships emit less CO_2 per ton-mile than other modes but have a more significant ecological impact due to their scale, they use bunker fuel, a cheap but highly toxic and polluting tar-like liquid (Akgül, 2024). Shipping emissions contribute to global warming by trapping heat, causing rising sea levels and extreme weather. Combustion of maritime fuel also releases SO_X, NO_X, and PM, leading to ocean acidification, marine biodiversity loss, and respiratory issues in coastal populations (Feng *et al.*, 2024). As an international regulatory organization, the International Maritime Organization (IMO) has taken stringent measures to comply with the provisions of the Paris Agreement (Ampah *et al.*, 2021). These measures are directly aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG13 (Climate Action), SDG7 (Affordable and Clean Energy), and SDG9 (Industry, Innovation, and Infrastructure) to provide a comprehensive framework for addressing global environmental, economic, and social challenges. In addition, the additional rules introduced by the European Union for maritime trade activities within its geographical borders, in addition to or independently of IMO rules, show that green shipping is being taken seriously from a supranational perspective (European Commission, 2020). Given that all industry stakeholders, particularly ship operators and ports, will be impacted by these developments, they must reassess their business models, adapt operations, and invest in necessary measures.

While green shipping regulations are often seen as a burden on maritime trade, they are also expected to influence countries' macroeconomic outlook (Lee and Nam, 2017). Just as the post-COVID-19 period saw disruptions in maritime transport, logistics costs, and trade due to container shortages—triggering global inflation—regions struggling with green shipping compliance may face similar trade impacts, affecting market supply. Therefore, maritime stakeholders must take necessary action.

Considering that maritime businesses face both challenges and opportunities in complying with stringent emission standards and adopting sustainable practices while trying to transition towards a low-carbon future, this study aims to review the role and impact of environmental regulations in shaping the green transformation of the maritime industry. Specifically, it seeks to review the effects of international and regional regulations (e.g., IMO decarbonization targets, EU-ETS) on the maritime industry, assess the implications for industrial productivity, operational strategies, and financial sustainability, identify challenges and opportunities that industry stakeholders face in adapting to these policies and provide recommendations for policymakers, ship operators, and industry leaders to navigate the green transition effectively. By addressing these objectives, the study contributes to the existing literature on maritime sustainability, offering a comprehensive evaluation of regulatory impacts and potential adaptation strategies.

The second part of the study examines post-Paris Agreement maritime regulations, emphasizing environmental sustainability and eco-friendly ships. The third section explores target-based and market-based measures in green transformation, highlighting related industrial threats and opportunities. The fourth section examines the industrial impact of regulations, focusing on productivity mechanisms, financial and regional aspects, contractual frameworks, and emerging opportunities. The study ends with conclusion.

2. GREEN SHIPPING REGULATIONS

Maritime trade made great progress in the 19th century when steam engines and large steel-hulled ships were built, and offshore cable networks and global transportation networks were established. In the early years, steamships struggled to compete with sailing ships due to inefficiency, but technological advancements eventually phased out sailing ships from maritime trade. With the rise in maritime trade demand, larger and more versatile ship designs with propulsion systems using petroleum-derived fuels began to dominate the maritime trade (Stopford, 2009). Both coal and petroleum, derived from ancient organic matter, contain carbon, leading to inevitable carbon-based gas emissions during combustion. Unfortunately, these carbon emissions are not even the tip of the iceberg.

Ships consume around 4 million barrels of heavy fuel oil per day, equivalent to 4% of total global oil production (Fridell, 2019). From a cost analysis perspective, the proportion of fuel costs in a ship's daily operational and capital expenditure is quite high (Stopford, 2009). However, the environmental impacts of the fuels consumed are now more frequently emphasized, as well as their cost. Given the highly polluting nature of these fuels, characterized by high levels of toxic chemicals, shipping does not fit seamlessly with environmental sustainability goals. Considering the emphasis on green transformation and stringent regulations implemented by the International Maritime Organization (IMO) and the European Union (EU), the goal of reducing greenhouse gas emissions to zero by 2050 has led to a significant shift in the maritime industry (IMO, 2023a). As of 2018, ships calling at EU ports are required to disclose their fuel and CO_2 emissions, and the regulation on the payment of carbon tax by ships calling at EU ports has also come into force, making it inevitable for shipping companies to take urgent measures in this regard (European Commission, 2024b).

2.1. Regulations for Reducing SO_X and NO_X Emissions

One of the biggest global environmental concerns today is air pollution from maritime transportation, and IMO, an international regulatory authority, updated the International Convention for the Prevention of Pollution from

Ships (MARPOL) 73/78 version in 1997 (IMO, 2024a). This update, which added the sixth annex to MARPOL, introduced rules for the Prevention of Air Pollution from Ships. With MARPOL Annex VI, Nitrogen Oxides (NOx) and Sulphur Oxides (SO_X) were initially taken into consideration as the main factors of pollution, and it was aimed to reduce emissions by developing rules and processes for the use of clean fuel in Emission Control Areas (ECA) (IMO, 2023b). On the other hand, measures such as Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index (EEDI) have been implemented to ensure fuel and energy efficiency. However, IMO did not include marine greenhouse gas (GHG) emission reduction in its regulatory framework until 2011. MARPOL Annex-VI Chapter 3 Rule-13 and Rule-14 contain restrictions on NO_X and SO_X emissions, respectively. Looking at the restrictions for NO_X emissions under Rule-13, ships are divided into three classes according to the years of production of their machinery. Tier-I refers to machinery manufactured between 2001-2011; Tier-II refers to machinery manufactured between 2011-2016; and Tier-III refers to machinery manufactured after 2016. There are different NO_X calculations according to the engine operating speeds (rpm) of the ships. All ships built between the specified dates must comply with these restrictions, and machines built before 2001 are not required to comply with these restrictions (IMO, 2024b). The strictest of these, 'Tier III', applies to main engines installed on ships built in 2016 or later operating in ECA regions (NECA) where NO_X is controlled. From January 2021, all ships in these regions must use mandatory main engine standards or equivalent NO_X emission reduction technologies to comply with NO_X emission levels. In 2016, IMO also included the Baltic Sea and the North Sea under NECA (Pape, 2020). Considering the fuel-sulfur content restrictions that must be complied with under Rule-14, two different types of restrictions are seen for the whole world and for the ECA regions. Before 01.01.2012, the sulfur content of fuel could not exceed 4.5% by mass worldwide. This was reduced to 3.5% as of January 1, 2012, and then to 0.5% as of January 1, 2020. In the ECA regions where SO_X is controlled (SECA), this ratio is even lower, and while oil sulfur content was limited to 1.5% before July 1, 2010, it has been limited to 1% since then and to 0.1% since January 1, 2015 (IMO, 2020). The European Union has also enacted IMO SO_X limits (Directive EU/2016/802) and has mandated the use of marine fuels with a maximum sulfur content of 0.1% in the EU SECA regions and set the same limit for ships calling at its ports. NO_X emission limits for EU countries are instead set under EU air quality standards for pollutants in ambient air (Pape, 2020). SO_X emissions are recognized to contribute to the formation of fine particles, which are harmful to humans due to their inorganic content. In this context, market participants have various alternatives to comply with the above-mentioned limits. These alternatives include the continued use of conventional heavy fuel oil (HFO), if scrubber technology that filters out Sulphur is installed on ships, synthetic fuels such as low Sulphur fuels (VLSFO, ULSFO) that are largely free of Sulphur, as well as alternatives such as Liquefied Natural Gas (LNG), Marine Diesel Fuels MDO, MGO (Al-Enazi *et al.*, 2021). However, Sulphur emissions are the tip of the iceberg and stringent regulations are aimed at reducing greenhouse gas (GHG) emissions.

2.2. Regulations for Reducing GHG Emissions

Greenhouse gases, defined as gases that trap heat in the atmosphere and increase the earth's temperature, include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other fluorinated gases. These gases can increase with human activities (e.g. fossil fuel use, industrial processes, agriculture) and increase the greenhouse effect, leading to problems such as climate change (Dong *et al.*, 2022). The Paris Agreement was adopted in 2015 at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change. At COP21, all countries on a global scale committed to greenhouse gas emission reductions after 2020. The Agreement entered into force on November 4, 2016, with the ratification of at least 55 parties, accounting for 55% of global greenhouse gas emissions. It is the first global agreement to enter into force just one year after its adoption (Republic of Turkey Ministry of Foreign Affairs, 2024).

As with the measures taken against other pollutants, the EU has taken its place among the parties taking the first steps as a "first mover" for CO_2 emissions. In this context, in 2015, it adopted a system for monitoring, reporting and verification of CO_2 emissions for maritime transport ("MRV Regulation" 2015/757/EU) and required reporting from ships over 5000 GRT calling at ports in the European Economic Area (EEA). Despite plans to harmonize with IMO measures, double reporting has continued since the launch of the global IMO DCS in 2019 (European Commission, 2024b). In 2019, the European Commission introduced the "European Green Deal (EGD)" to address climate challenges with the goal of a carbon-neutral EU by 2050. The EGD, a comprehensive strategy adopted by the European Union to tackle climate change and environmental sustainability, aims to reduce the EU's greenhouse gas emissions to net zero by 2050. However, the EGD also includes far-reaching objectives such as promoting economic growth, investing in green technologies, creating jobs and ensuring social justice. The EGD is one of the EU's key commitments to sustainability and combating climate change, with various instruments such as budget, legislation, incentive mechanisms and innovation to achieve these goals (European Commission, 2020). To turn the political commitment to the EU's carbon-neutral target into a legally binding obligation, the European Climate Act was adopted on June 30, 2021 (Presidency of the European Union, 2024). In July 2021, the European Commission presented a set of complementary and interlinked proposals as part of the "Fit for 55" package to align the EU's climate, energy, land use, transport and taxation policies to reduce net greenhouse gas emissions by at least 55% by 2030 (European Commission, 2021). This package includes the Emission Trading System (ETS), the Carbon Border Adjustment Mechanism (CBAM), the Energy Taxation Directive (ETD), and the Renewable Energy Directive (RED). includes a number of EU regulations affecting maritime transport, such as the Alternative Fuels Infrastructure Regulation (AFIR) and, most recently, the Maritime Fuel Initiative (FuelEUMaritime) (European Commission, 2023a). As visualized in Figure 1, the EU aims to reduce the carbon footprint of the maritime industry by up to 80%, starting with a 2% reduction in 2025 and increasing every five years until 2050, and to promote the use of renewable and low-carbon fuels in the industry.

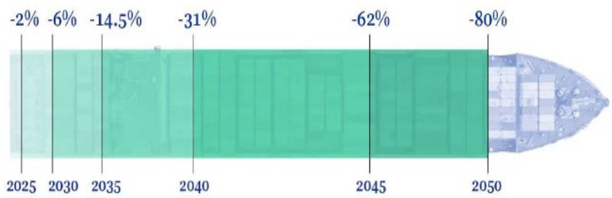

Fig.1 EU GHG Emission Reduction Target

In May 2023, the EU further extended the scope of regulation to transit ports up to 300 nautical miles from its borders, with effect from 1 January 2024. This is intended to prevent illegal voyages to ports outside the EU to avoid ETS payments (DNV, 2023). Achieving this emission limit in the next decade is crucial for Europe to become the world's first climate-neutral continent by 2050, making the "European Green Deal" a reality.

In response to the EU Climate Law requirements to reduce Europe's net greenhouse gas emissions by at least 55% by 2030, the 'Fit for 55' package was prepared in July 2021, then updated to consider renewable energy and energy efficiency issues in the REPowerEU plan to increase Europe's energy security, which emerged with Russia's war in Ukraine. The final legislative package is expected to reduce the EU's net greenhouse gas emissions by 57% by 2030 (European Commission, 2023a). The package aims to establish a common EU regulatory framework to encourage an increased share of renewable and low-carbon fuels in the fuel mix of international maritime transport while ensuring the smooth operation of maritime transport without distorting the internal market. Furthermore, the European Commission is finalizing the EU taxonomy criteria for the decarbonization of ships to classify ships and facilitate compliance checks for sustainable marine fuels and intends to revise the criteria after 2025 based on industry feedback (European Council, 2023b).

2.3. Green Ship

The term "Green Ship" can be scientifically defined as a vessel designed to minimize environmental impact, characterized by low or zero emissions, and constructed in compliance with international regulations established to mitigate climate change (Sherbaz *et al.*, 2015). Beyond its definition, the green ship concept represents a strategic shift in maritime transportation, affecting competitiveness, financial viability, and regulatory compliance (Branza, 2023). Green ships are no longer just an environmental ambition; they have become an operational necessity for ship owners and operators seeking to maintain access to global markets (Shi and Gullett, 2018). Within the scope of making a ship environmentally friendly, being a green ship depends on the operational status of the ship. However, there are ways to improve environmental performance, including reducing fuel consumption per ton-mile by implementing speed strategies (Norlund and Gribkovskaia, 2013). Reducing ship speed can result in significant fuel savings of up to 60% (Chang and Chang, 2013). However, actual savings vary greatly depending on ship type, size and weather conditions (Taskar and Andersen, 2020). Optimizing the hull and propeller design through improvements can also contribute to reducing fuel consumption at optimum speed (Allal *et al.*, 2018; Nelson *et al.*, 2013). In addition to propulsion, Molland (2014) emphasizes the importance of operational practices such as appropriate trim, speed and weather routing in reducing fuel consumption. Another option is for the industry to use more alternative fuels such as electricity, hydrogen, ammonia, and biofuels to achieve net zero emissions targets (Economist, 2021; IEA, 2024). The transition to environmentally friendly alternative fuels such as liquefied natural gas (LNG) and methanol is an important step towards becoming a green ship. Hydrogen is also expected to emerge as a potential fuel source, offering numerous benefits for the foreseeable future.

From a financial perspective, ship owners investing in green technologies gain preferential access to green financing mechanisms such as sustainability-linked loans and green bonds (Rebelo, 2020). Also, evidence confirms a price premium for eco-ships in the second-hand container market, with financial investors showing a stronger inclination toward these vessels compared to operational buyers (Jia *et al.*, 2024). In contrast, vessels failing to meet emission criteria may experience higher operational costs, restricted port access, and declining asset values due to non-compliance. Furthermore, cargo owners and charterers are increasingly integrating environmental performance metrics into contractual agreements, making sustainability a key factor in business decisions (Pereira, 2025).

3. SIGNIFICANT MEASURES WITHIN THE SCOPE OF GREEN SHIPPING REGULATIONS

Regulations based on environmental, social and corporate governance (ESG) principles that have come into force in recent years stand out as a key factor shaping the strategies and operations of shipping companies worldwide. In addition to the obligations imposed by these regulations, as these principles have become a priority in the global business environment, shipping companies have started to focus more on ESG principles to create more value and reduce risks in the long term (Tsatsaronis *et al.*, 2024).

Environmental sustainability is at the forefront of ESG initiatives in the maritime industry. As the maritime industry accounts for a significant portion of global carbon emissions, shipping firms are under increasing pressure to reduce their environmental footprint. It can be stated that the regulations mentioned in the previous section for the maritime industry within the scope of combating climate change have become a serious tool in the process of compliance with the environmental dimension of ESG principles. In this adaptation process, companies are investing in renewable energy technologies such as hybrid propulsion systems and wind-assisted technologies to increase fuel efficiency and reduce emissions. In particular, the adoption of alternative fuels such as biofuels, hydrogen, LNG, methanol, etc., holds promise for further reduction of GHG emissions in the maritime industry. Shipping companies are exploring collaborations with stakeholders across the value chain, including fuel suppliers, shipbuilders and port authorities, to accelerate the transition to cleaner energy sources and achieve ambitious decarbonization targets. This section outlines what these measures entail.

3.1. Goal-Based Measures: EEDI, EEXI and CII

To achieve the zero-emission target, IMO has developed methods to measure technical and operational performance. Energy Efficiency Design Index (EEDI), Energy Efficiency Index of Existing Ships (EEXI) and Carbon Intensity Indicator (CII) are among the important measures developed within the framework of decarbonization efforts in the maritime industry. While EEDI is an international regulation established by the International Maritime Organization (IMO) to encourage the adoption of energy-efficient ship designs and is a criterion required for new-build ships contracted after January 1, 2013 (Tokuşlu, 2020), effective from January 1, 2023, all existing ships of 400 GRT and above, regardless of the delivery date, are required to calculate EEXI as an energy efficiency indicator. The main purpose here is to encourage ships to be designed in a way to reduce carbon emissions (Bayraktar and Yuksel, 2023). Firstly, the EEXI values of existing ships are calculated, and then this value is compared to the required EEXI value according to a certain formula. Ships that meet or exceed the EEXI requirements are considered more environmentally friendly and receive favorable treatment under international regulations. With the EEXI regulation, ship operators are expected to assess the energy efficiency of their ships and take measures to improve performance and reduce emissions to comply with the prescribed EEXI requirements. Measures may include retrofitting existing ships with energy-saving technologies, optimizing operational practices and improving propulsion systems to achieve greater fuel efficiency (ClassNK, 2022).

An EEXI calculation is required for all ships of 400 GRT and above, except for advanced icebreakers, floating production storage and offloading units (FPSO), non-propeller vessels, diesel-electric, turbine or hybrid propeller vessels without conventional propellers, which are defined as Polar Code Category A. The purpose of this calculation is to calculate how many grams of CO_2 emissions a ship produces while moving 1 ton of cargo 1 nautical mile. According to the formula where a specific value is calculated for each ship, the CO_2 factor of the fuel used, the specific fuel consumption of the main engine and generators when operating at a certain percentage, the kW of the machinery on board, the maximum loading capacity of the ship and the EEXI reference speed are considered. Companies should calculate these five parameters very well and provide them as soon as possible. For specific fuel consumption, it would be appropriate to use the approved values from the parameters in the technical file. Otherwise, reference values published by IMO depending on the ship type and tonnage can also be used, but since these values may cause the EEXI calculation to be lower than expected to a certain extent, it is necessary to access the ship's specific information as much as possible. As a matter of fact, the more accurate the information is, the more accurate the EEXI will be. Similarly, the reference speed can be obtained from the tank test reports from the shipyard where the active ships are built. Otherwise, these data can be obtained by speed trial sailing after the ship is brought to the ideal position after the first drydock. In cases where this is not possible, IMO tables can be taken as reference. If a ship with an EEDI value is above the required EEXI value compared to the value written in the Energy Efficiency Certificate, necessary measures should be taken (ClassNK, 2021).

CII, which is the most emphasized by market players and includes the most stringent measures, stands out as the first measure proposed by IMO within the scope of the Greenhouse Gas Strategy, which aims to reduce the carbon intensity of international maritime transportation (Bayraktar and Yuksel, 2023). The CII indicator, which measures how efficiently a ship transports cargo or passengers, is given in terms of cargo carrying capacity and CO_2/gram emitted per nautical mile. CII is one of the most important metrics for energy efficiency in maritime activities. As shown in Figure 2, its thresholds are becoming more stringent over time until 2030.

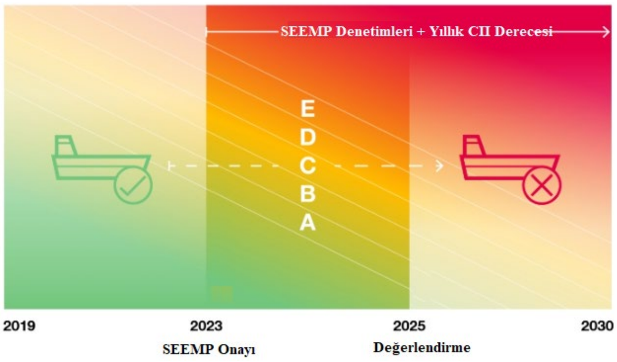

Fig.2 CII Classification and Distribution by Years

In practice, this means that a ship with an A rating may, over time, degrade and become a 'B' rated ship or worse. If the ship is rated 'D' or 'E', the ship operator is required to submit a remedial plan to show how the required index (C or above) will be achieved. This process applies to all ships over 5,000 GT (MAN Energy Solutions, 2024).
While meeting the required EEXI requirement once will be sufficient for the economic life of the ship, CII requires continuous auditing. The main purpose of CII is to check how green the ship's operation is. Unlike EEDI and EEXI, which focus on energy efficiency, CII specifically targets carbon emission intensity by measuring the amount of CO_2 emitted per unit of transport work such as ton-mile or passenger-mile (Garbatov *et al.*, 2023). Ship owners and operators are required to monitor and report the carbon intensity of their ships. Indeed, non-compliant vessels will be subject to potential penalties or operational restrictions. The implementation of the CII is expected to incentivize investment in cleaner technologies, alternative fuels and operational practices to reduce emissions and enhance the sustainability of the maritime industry. These measures aim to accelerate the industry's adaptation to the decarbonization process by promoting energy efficiency, reducing GHG emissions and encouraging innovation in ship design, operation and management (Sun *et al.*, 2023). Compliance with regulations such as EEDI, EEXI and CII is crucial to ensure the sustainability and competitiveness of the global shipping industry in a carbon-constrained future.

3.2. Market Based Measures

Governments and businesses are increasingly recognizing the importance of carbon pricing for the transition to a low-carbon economy. Carbon pricing is a market-based measure (MBM) used to limit emissions and is gaining momentum worldwide. Currently, 40 national and 25 sub-national jurisdictions are implementing carbon pricing. These initiatives cover 8 gigatons of CO_2 emissions, equivalent to 15 percent of global greenhouse gas emissions. Of the 46 implemented or planned carbon pricing initiatives, 23 are carbon taxes, and 23 are Emissions Trading Systems (ETS). For example, British Columbia implemented a revenue-neutral carbon tax approach covering 70 per cent of total emissions in 2008. In other words, all revenue generated is paid back to taxpayers, including personal income tax, corporate tax and property tax. ETS is also a market-based measure to reduce emissions. In addition to countries' own ETS initiatives, alternatives such as international co-operation and market consolidation are also being examined. In some regions, mixed systems where carbon tax and ETS are used together are preferred (UNFCCC, 2024).
Among the regulations included in the 'Fit for 55' package, which stands out within the scope of 'The European Green Deal', MBM is also considered as a part of the solution. In particular, the inclusion of maritime transport in the EU-Emission Trading System (EU-ETS) stands out as one of the important mechanisms developed in this context (Meng *et al.*, 2023; Psaraftis *et al.*, 2021). EU-ETS is seen as an effective MBM in combating climate change. MBMs operate according to the 'polluter pays principle' and emitters cover the cost of their emissions (Marrero and Martínez-López, 2023). In summary, in case of a quota exceedance, the carbon tax will be paid per ton until the point where the 'Carbon Allowance' is requested. As shown in Figure 3, according to the EU-ETS, 50 per cent of emissions from voyages starting or ending outside the EU are included in the emissions calculation (allowing the third country to decide on the appropriate action for the

remaining share of emissions), 100 per cent of emissions between two EU ports and 100 per cent of emissions when ships are within EU ports (European Commission, 2023b).

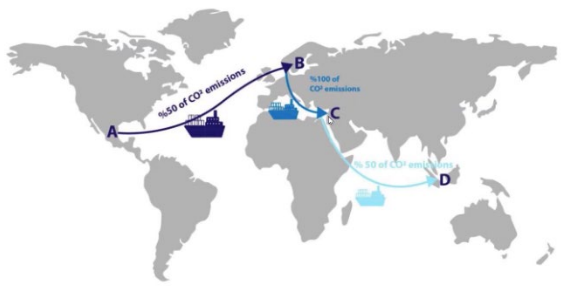

Fig.4. EU-ETS Coverage

There are questions about what the EU-ETS means and how it will be applied to maritime transport in the future. The ETS is not a new regulation but has a history dating back to 2005. Rather, the maritime industry is building on the existing mechanisms according to a specific timetable (European Commission, 2024). In addition, some changes are being made in accordance with the mobility of ships, including the MRV mechanism.

There are very serious costs in this mechanism, which will expand over time. Shipping companies must comply with MRV regulations from today and the financial consequences are estimated at around EUR 10 billion per year until 2026. With disagreements on actual emissions and MRV reporting, existing contracts and long-term lease agreements need to be renegotiated to cover emissions costs. Real-time verified emission data is crucial for recent contractual agreements.

Emissions trading can be explained with an example. Assume that companies A and B both produce 100,000 tones of CO_2 emissions per year. Assuming that the competent authority gives each of them 95.000 tonnes of carbon permits, 'The Cap', both companies will look for ways to close the 5.000 tonnes deficit. In this case, the companies will have the choice to reduce their current emissions by 5000 tonnes, or to buy 5000 tonnes of carbon quotas from the market, or to take a position somewhere between the two alternatives (The Trade). They will need to compare the cost of each before deciding which option to take. Let us assume that the price of carbon in the market at that moment is €20 per tonne of CO_2. Suppose company A calculates that it will cost it €10 per tonne to reduce its emissions. Let's assume that company A decides to reduce 10,000 tonnes, motivated by the low cost compared to the market price. Suppose that company B, on the other hand, calculates that the cost of carbon emission reduction costs is €30 per tonne, i.e. higher than the market price, and therefore decides to buy quotas from the market instead of reducing emissions. In this case, company A will spend €100 000 to reduce its emissions by 10 000 tonnes at a cost of €10 per tonne, but will then sell the 5 000 quotas it no longer needs at a market price of €20/tonne, generating a revenue of €100 000. This would mean that the costs of emission reduction are fully offset by selling quotas. Whereas without the emissions trading system, company B, which would have to incur a net cost of €50,000 assuming that it would reduce emissions by the required 5,000 tonnes, would spend €100,000 to buy 5,000 tonnes of quota at a market price of €20/tonne. Without the flexibility provided by the ETS, it would have to reduce its emissions by 5,000 tonnes at a cost of €150,000. Therefore, emissions trading provides a total cost saving of €100,000 for the companies in this example. Since Company A has chosen to reduce its own emissions, even if Company B has not reduced its own emissions, it will be reduced to the required level with the quota purchased. As seen in this example, with EU-ETS, emissions will be reduced at the lowest possible economic cost (European Commission, 2009).

4. INDUSTRIAL EFFECTS OF GREEN SHIPPING REGULATIONS

The implementation of green shipping regulations has a multifaceted impact on the productivity of the maritime industry. While these regulations aim to drive sustainability, they also introduce operational and financial challenges that influence industrial productivity (Filippopoulos *et al*., 2024).

4.1. Mechanisms of Regulatory Impact on Industrial Productivity

Compliance with stringent environmental regulations necessitates significant financial investments, affecting the cost structures of shipping companies. Regulations such as the IMO's Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), as well as the EU Emissions Trading System (EU-ETS), require vessel owners to adopt cleaner technologies, install energy-efficient equipment, or switch to low-emission fuels. These compliance costs—ranging from retrofitting expenses to the purchase of carbon credits—can lead to short-term productivity declines as firms allocate resources to regulatory adaptation rather than operational efficiency. For smaller shipping firms and those operating older fleets, these financial burdens may reduce their competitiveness, leading to potential market exits. Under target-oriented measures, existing vessels are expected to meet minimum standards set according to their technical characteristics and operational profiles. The CII is more important for market players as it includes the obligation to comply with increasingly stringent levels throughout the economic life of the ship. As a matter of fact, the fact that the required level of energy efficiency is exceeded once and there is no obligation to renew the certificate once it is obtained causes the focus to be mainly on CII. Moreover, while EEXI is based on the theoretical capacity, empty sailing within the scope of CII will have a negative impact. Therefore, the need to minimize ballasted voyages will arise. This may have another negative impact on ship management. Ships in D and E classes will face additional costs such as higher taxes and insurance. Since the average fuel consumption and speed in the current period are taken into consideration while determining the classification, if the ships in these classes cannot take the necessary actions, they also carry the risk of being dropped from these classes and being banned from maritime trade activities with the entry of new construction ships into the market.

4.2. Effects by Ship Tonnage

Regulatory changes influence the competitive landscape of the maritime industry by favoring firms that can adapt more efficiently. Larger shipping companies with greater financial flexibility are better equipped to absorb compliance costs, integrate sustainable technologies, and secure green financing. In contrast, smaller firms with limited capital may struggle to comply, leading to market consolidation as weaker players exit or merge with larger entities. The fact that the EEXI account is mandatory for all ships of 400 GRT and above while the CII account is mandatory for ships of 5000 GRT and above shows that small tonnage ships are exempt, but small tonnage ships will also be indirectly affected by this practice. Considering that small tonnage vessels are below 5000 GRT, although these vessels seem to be exempt from the CII obligation, they face a growing risk of being excluded from chartering opportunities as sustainability-conscious cargo owners and charterers prioritize lower-carbon transportation options. Moreover, stricter environmental policies in key maritime regions, particularly in European Union ports, pose additional challenges for small tonnage ships. Companies required to calculate carbon footprints throughout a product's lifecycle may avoid working with high-emission ships, significantly impacting the industry. Charterers increasingly request emission data from ship operators, a trend expected to grow. Although exempt, small tonnage operators should address CII. Stricter regulations will likely emerge by 2030, a key milestone for EU and IMO targets.

4.3. Effects by Regional Context

The effectiveness of compliance varies across regions and vessel types, with developed maritime hubs better equipped to meet standards (Akac *et al.*, 2023). Maritime hubs like Northern Europe, Japan, and South Korea enforce stricter regulations and have better access to technology, ensuring easier compliance with CII and EEXI. Developing regions, such as parts of Africa and Southeast Asia, face significant financial and technical barriers (Baştuğ *et al.*, 2024). European ports have made significant progress in adopting various sustainability initiatives compared to North American and Asia Pacific ports (Hossain *et al.*, 2021). Ports are increasingly integrating renewable energy sources, improving energy efficiency, and implementing new infrastructure to reduce environmental impact (Sadiq *et al.*, 2021). However, a gap exists between developed and emerging countries in terms of energy management and environmental policies (Durán *et al.*, 2022).

4.4. Financial Effects

There is a major financial challenge related to the zero-emission journey of the industry. With the entry into force of the EU-ETS, a price will have to be paid for maritime emissions. Shipping companies must annually report verified emission data for MRV compliance, purchase carbon quotas from the market and submit them to the responsible national authority within the EU. The aim of the EU ETS regulation is to transfer the cost of emissions to the polluter, i.e. the end user. Transport companies are required to ensure that emission quotas are transferred along the value chain in order to avoid the financial burden. Owners must be ready to submit their quotas to national authorities annually and provide verified emissions data to ensure compliance.

The economic dimension is crucial for investment decisions in innovative ship technologies (Raza, 2020). As the transition to cleaner fuels or technologies often requires large initial investments, many shipping companies find it difficult to secure the necessary financing for these initiatives. As environmental requirements tighten and the age of ships increases, it will become increasingly difficult to choose between retrofitting or newbuilding, given that the technical value of ships will decrease and the cost of refurbishment will increase. Besides uncertain returns on investment, other threats include limited access to affordable finance, lack of adequate investment incentives, high development costs for infrastructure, technology-related risks, volatile market and fuel prices, competitive pressures and lack of uniform regulations. While the short-term costs of this transformation are prominent, it is also useful to focus on the long-term benefits of alternatives. Looking at the studies carried out in this context, Bui *et al.* (2021) introduced a life cycle cost analysis (LCCA) for emission-reducing ship machinery, while Yalamov *et al.* (2023) used NPV scenarios to evaluate dual-fuel adoption. A case study on South Korean container shipping suggests that LNG fuel retrofitting may be the most favorable option for meeting EEXI and CII requirements (Ahn *et al.*, 2023). Their findings suggest that due to economic uncertainties, LNG price volatility, and CO_2 taxation, shipowners should secure long-term LNG contracts to sustain GHG reduction efforts.

Methanol and LNG are viable alternatives for emission reduction (Lagemann *et al.*, 2022), with LNG allowing cost-effective retrofitting to ammonia. These trends align with current vessel orders. Zhao *et al.* (2023) indicate that LNG will dominate in the short term, while ammonia and hydrogen will be key transition fuels. Retrofitting, efficient navigation, and shore power are essential for decarbonization. Liu *et al.* (2022) found LNG's NPV lower than MGO's, recommending MGO retrofitting for maximum economic benefits. Additionally, compliance-driven restructuring extends to port operations and supply chain logistics, as regulatory-compliant firms seek partnerships with green ports and eco-friendly logistics providers. This shift alters the traditional market dynamics and redefines competitive advantages within the industry.

While the EU is often seen as the spearhead of maritime decarbonization efforts, it is important to recognize the vital role that non-EU countries play in shaping the sustainable future of this industry. As significant contributors to shipping emissions, non-EU countries hold the key to steering the industry towards environmentally responsible pathways. However, financing options for shipping decarbonization initiatives present challenges that require innovative strategies. A net zero emissions target has significant financial implications for shipowners and operators, particularly in terms of the large investments required to transition to a greener shipping fleet.

Achieving the set targets will also come at a cost to the end user. Indeed, the cost of using the new fuels will be passed on to shippers who commit to decarbonize their supply chains. Theoretically, if consumers choose Net Zero products, Net Zero supply chains will be achieved. In practice, consumer choice alone will not be enough. To make green fuels competitive, the cost of heavy fuel oil needs to increase, which will inevitably lead to products becoming more expensive, which means inflation.

4.5. Effects on Charter Contracts

There are concerns about existing contracts in relation to MRV. Long-term charter contracts will need to be renegotiated. Especially in the measurement of actual emissions from a ship, disputes may arise, and the perspective of the charterer and the owner may differ. Although legal compliance with the system will take place according to a specific timetable, data will need to be available in 2024, as the cost of waiting in the commercial world can be high and given that there are contracts that need financial settlement as early as possible. Therefore, the need for real-time verified emission data will increase. Otherwise, there will be problems in contracts with existing partners, it will not be possible to take advantage of new business development opportunities, and ultimately there will be an increase in business and financial risk. Furthermore, the risk of operating some non-compliant vessels may translate into legal implications that need to be addressed for the entire fleet of vessels under management.

4.6. Opportunities

Achieving the net zero carbon emission target for the maritime industry also offers significant opportunities for national economies. For example, newbuilding investments incentivized by emission regulations certainly create a significant economic impact, especially for countries with a large share in the world shipbuilding activities. South Korea, which has highly developed technological competitiveness in the face of high value-added, environmentally friendly shipbuilding orders, has increased its global market share to 37 per cent and has become the leader with a 54 per cent market share, especially in LNG propulsion (MOTIE, 2023). The development of policies that provide added value from all logistics processes, especially transport and storage systems, regarding the supply of these clean fuels will make a significant contribution to the economies of countries.

While studies on various clean fuel alternatives as potential substitutes for dirtier marine fuel continue, new techniques and technologies are also being explored (Bouman *et al*., 2017). It is observed that supply options are shaped depending on demand. In particular, a thriving market is emerging for technology companies dedicated to developing green shipping practices (Md Moshiul *et al*., 2021). In this context, companies working on the development and commercialization of technologies can significantly benefit from the growth of new industry initiatives aimed at reducing the environmental impact of global maritime trade activities with more than 100,000 ships. As highlighted by Schuler (2021), the total cost of modernizing the global merchant fleet to meet 2050 emission targets is estimated to be around USD 2 trillion. There is a total market of USD 3.4 trillion for businesses that can offer clean technology solutions to help maritime companies meet these new regulatory requirements. Therefore, supporting enterprises/initiatives in the direct or indirect industries that will operate in this context with various incentive mechanisms can provide significant gains to the national economies in the long term.

In addition, various financial instruments with a green maritime theme are also being developed. Among the most important developments in this regard, instead of bonds among traditional borrowing instruments, the 'green bond' developed to support projects within the scope of green transformation now stands out as an important financial substitute (Rizou, 2023). Green bonds can make significant contributions for countries in increasing the efficiency of financial markets. Especially considering the capital-intensive structure of the maritime industry, it can be stated that it will be an important tool in meeting the external resource needs of market players at affordable costs.

5. CONCLUSIONS

In accordance with the Paris Agreement within the scope of combating climate change, countries and international regulatory authorities have taken various initiatives and enacted regulations containing strict measures and legal obligations to achieve the targets set. IMO, which has an important mission to bring maritime trade to the desired structure, is also taking important steps in this context. GHG regulations, which came into force after the NO_X and SO_X regulations, have raised the bar one more level. Green maritime regulations mark an important point in the evolution of maritime trade. In response to increasing environmental regulations, this study highlights the critical role of policy, technology, and market-based mechanisms in shaping the green transformation of the maritime industry. While regulatory compliance presents financial and operational challenges, proactive adaptation through sustainable investments and strategic planning can ensure long-term resilience and competitiveness. It seems that all stakeholders of the industry, especially ship operators, will try to exist on a playing field that they have not encountered before. Therefore, it is necessary to understand what is at stake and to take the necessary steps without delay. This study emphasizes the multifaceted impacts of green maritime regulations on various aspects of the maritime industry, from operational practices to economic dynamics.

Within the scope of green transformation, governments need to develop various incentive mechanisms for the maritime industry. Among these, establishing a quota for the maritime industry while granting renewable energy licenses for the maritime industry to be less affected by carbon taxes can make a significant contribution. As a matter of fact, many large manufacturing companies aim to use their quotas in their own production facilities by investing in renewable energy facilities to convert their CO_2 positive quotas into negative quotas. Allocating quotas for the maritime industry can protect it from the high costs of purchasing carbon quotas from the market. Ports may also need to be prepared or incentivized accordingly.

Especially in developing countries such as Türkiye, focusing on some niche areas can be considered as a strategic step. In this context, studies on environmentally friendly engines for special purpose vessels such as fishing motors, recreational boats, tugboats and yachts can be increased. Therefore, scientists should be supported within the scope of R&D studies and support mechanisms should be provided without delay. In this respect, it is especially important for developing countries to receive the highest possible share from the fund to be established at IMO.

It should not be forgotten that there is a serious threat to the maritime trade fleets of the countries. For example, it can be considered that Türkiye's maritime trade fleet mainly consists of old and small tonnage general cargo ships and if this fleet succumbs to the green transformation process, foreign trade companies will incur high costs in transporting their cargoes and will have a negative impact on the sustainability of foreign trade. Therefore, it may provide significant gains for the top management of the companies to take measures rapidly against these developments, to form units within their own organizations, and for small companies, which are in the highest risk group, to act in clusters. In order to make sustainable practices financially viable and desirable for the maritime industry, it will be necessary to address these complex issues and develop supportive government frameworks, industry-wide co-operation and new financing models. The feasibility of such models depends on the financial structure of firms and the regulatory frameworks they operate within. For large shipping firms in developed economies, green bonds, sustainability-linked loans, and government-backed subsidies provide viable funding mechanisms. However, for small and medium-sized enterprises (SMEs) or operators in developing regions, access to capital remains limited. Therefore, financing models should include flexible instruments such as public-private partnerships (PPPs), carbon credit trading schemes, and regional funding pools that reduce the financial burden on smaller market players. These approaches can be tailored to specific regulatory and economic contexts, making them more widely applicable. The generalizability of the proposed solutions is crucial in ensuring that different stakeholders—ranging from policymakers and shipowners to financial institutions—can adapt these strategies to their needs. While some measures, such as compliance-driven retrofitting and digital optimization, are universally applicable, others, like alternative fuel investments, depend on infrastructure availability, economic incentives, and market readiness. Future research should further explore scalability models for green financing, assess the long-term economic viability of alternative fuels, and analyze how policy interventions can support equitable decarbonization across diverse maritime regions. By integrating regulatory, financial, and technological perspectives, this study provides a structured approach to understanding and addressing the challenges of green shipping. Moving forward, interdisciplinary research and collaboration between industry stakeholders will be essential to refine these strategies and facilitate a sustainable maritime future.

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