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Koundouri, Phoebe and Alamanos, Angelos and Deranian, Christopher and Garcia, Jorge Andres and Nisiforou, Olympia

Athens University of Economics and Business, 10434 Athens, Greece, ATHENA RC, UN SDSN Europe, 10434 Athina, Greece, Department of Technology, Management and Economics, Denmark Technical University (DTU), Kongens Lyngby, Denmark, Independent Researcher, Berlin 10243, Germany, Fulbright Foundation in Greece, Athens 10674, Greece, The Water Institute, University of Waterloo, ON, Canada, Cyprus University of Technology, Limassol, Cyprus

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Authors

Phoebe Koundouri [1,2,3] *, Angelos Alamanos[4], Christopher Deranian[1,5], Jorge Andres Garcia [6] and Olympia Nisiforou [7]

Affiliations

Athens University of Economics and Business, 10434 Athens, Greece[1]

ATHENA RC; UN SDSN Europe, 10434 Athina, Greece[2]

Department of Technology, Management and Economics, Denmark Technical University (DTU), Kongens Lyngby, Denmark[3]

Independent Researcher, Berlin 10243, Germany[4]

Fulbright Foundation in Greece, Athens 10674, Greece[5]

The Water Institute, University of Waterloo, ON, Canada[6]

Cyprus University of Technology, Limassol, Cyprus[7]

***** Correspondence: pkoundouri@aueb.gr

Abstract

The Greek maritime sector, one of the largest in the world, faces multiple economic, environmental and development challenges, requiring careful long-term investment decisions. In this paper we present the application of a free, open-source Investment Decision Support tool we have developed, the MaritimeGCH, applied for the Greek fleet. We quantify the effect of two main interventions for a cost-effective carbon abatement, under the recent EU environmental regulations: the implementation of mature on-ship emission reduction technologies and transition scenarios to cleaner fuels. While significant emissions are achievable, even ambitious interventions fall short of fully decarbonizing the sector by 2050. This suggests that a more unified set of policy solutions are needed to achieve the national commitments.

Introduction

1.1 Towards sustainable shipping

The shipping industry is a critical component of global economy and trade, responsible for transporting over 80% of the world’s goods (*1*). However, it is also a significant contributor to global greenhouse gas (GHG) emissions, accounting for approximately 2-3% of total emissions annually (*2*). These emissions primarily stem from the combustion of fossil fuels in ships’ engines, with carbon dioxide (CO_2) being the dominant pollutant. Despite being a key enabler of the global economy, the sector’s reliance on high-emission fuels has hindered efforts to align with international climate goals. Historically, the shipping industry has largely operated with minimal regulation concerning environmental impact, with emissions reduction efforts gaining momentum only in recent decades. In the early 2000s, the International Maritime Organization (IMO), the UN body responsible for regulating international shipping, began to acknowledge the need for action on emissions, primarily due to growing concerns over climate change. In 2008, the IMO introduced the first mandatory global regulations on emissions, known as the Energy Efficiency Design Index (EEDI), aimed at reducing the carbon intensity of ships. However, the industry's reliance on low-cost, high-emission fuels persisted, and more comprehensive regulatory frameworks emerged slowly. In July 2023, the IMO adopted a revised greenhouse gas reduction strategy, aiming to reach net-zero emissions by or around 2050. The strategy includes indicative checkpoints to reduce total GHG emissions by 20–30% by 2030 and 70–80% by 2040, relative to 2008 levels (*3*). Despite these efforts, the pace of decarbonization has been slower than anticipated. The global nature of the shipping industry, with its complex network of international regulations, trade routes, and diverse stakeholders, has created challenges in implementing uniform decarbonization strategies, further slowing progress (*4*). In particular, the shipping industry faces unique decarbonization challenges, including technological constraints, economic significance, increasing demand for shipping services, new and stricter environmental regulations, and the global nature of its operations.

Recently, metrics established by the IMO have helped to benchmark environmental performance for future regulation. The Carbon Intensity Indicator (CII) was introduced by the IMO as part of its strategy to reduce GHG emissions from ships (*3*). Adopted in 2021 and effective from January 2023, the CII aims to measure and regulate the carbon intensity of ships, which refers to the amount of CO_2 emitted per unit of transport work (*3*), based on the Annual Efficiency Ratio (AER). The AER, which has been in use since the early 2010s (*5*), measures CO_2 emissions per unit of transport work (e.g., per tonne-mile) over a year, calculated as the ratio of annual CO_2 emissions to annual transport work (*6*). Another important European regulation is the Emissions Trading System (ETS). While the ETS launched in Europe in 2005, only since January 2024 has been expanded to include the maritime sector, mandating an 80% reduction of the current emissions at EU-level by 2050. The ETS aims to reduce GHG emissions by setting a cap on the total amount of specific GHGs that can be emitted by entities covered by the system (*7*). So, since last year, maritime transport operators are required to monitor and report their CO_2 emissions to receive (or purchase) emission allowances, which they can trade with other operators. FuelEU Maritime is a regulation within the European Union's "Fit for 55" legislative package aimed at reducing greenhouse gas (GHG) emissions in the maritime sector. It mandates a progressive reduction in the GHG intensity of the energy used by ships, targeting a 2% reduction by 2025 and up to 80% by 2050. This regulation promotes the use of renewable and low-carbon fuels and clean energy technologies for ships, supporting the EU's broader goals of reducing emissions by 55% by 2030 and achieving climate neutrality by 2050. FuelEU applies to commercial vessels over 5,000 gross tonnes operating within the European Economic Area (EEA) and partially to voyages between EEA ports and third countries (*8*).

Following these regulatory changes aiming to net-zero, along with the inherent techno-economic constraints of maritime operations, and the need to cover increasing demands in shipping services, the sector faces an unprecedently complex situation. The use of integrated models has been the most common way to address such situations, trying to balance certain goals under constraints. Eide et al. (2013) projected shipping's CO_2 abatement potential until 2050 according to an extended techno-economic modeling framework with alternative fuels scenarios (*6*). While many studies have explored maritime decarbonization in the context of these policies, very few have simulated the potential effects of the recent EU ETS policy in early 2024.

In this research we fill this gap by presenting an investment decision support tool to evaluate the implications of techno-economic and regulatory factors, under decarbonization goals for 2050, using the Greek fleet as an application example. The shipping sector is particularly important for Greece, stemming from a deep-rooted tradition of maritime expertise and a strategic focus on global shipping markets, positioning it as a crucial component of international trade and economic stability (*9*). The country is the global leader in deadweight tonnage (DWT), with approximately 18% of global capacity, and a fleet capacity of approximately 427 million DWT. At the moment, Greece must accommodate rising shipping demand while complying with the recent IMO's targets and the EU ETS. Under the recently revised Greek National Energy and Climate Plan (NECP), there is no specific guidance on how the maritime sector will decarbonize and since the EU ETS regulation in 2024, there is still no national plan for fleet decarbonization (*10*). Greek shipowners have backed the ideas of a $5B Research and Development (R&D) fund paid by the shipowners for reducing CO_2 emissions and to invest in new technology research (*11*). Meanwhile, global decarbonization goals stress the need for consideration of cleaner fuels, within a smooth transition of replacing currently used conventional fuels. This transition consequently binds Greek shipowners to attain new global benchmarks on green supply chains (*12*). It is imperative to tackle this policy void using a science-supported approach, model-driven, demonstrating cost, technology, and timing repercussions for the Greek fleet. Our analysis is based on a novel Decision Support System, the MaritimeGCH. It explores techno-economic factors, alternative fuels, and operational emission-reduction measures along with modern socio-economic considerations in terms of shipping demand, under the recent EU policies (i.e., the EU ETS) and its associated economic parameters to achieve a realistic and holistic view of fleet decarbonization.

1.2 Capturing the complexities in shipping through integrated models

The general problem described in the previous section, namely meeting shipping demands under techno-economic and regulatory constraints, can be mathematically expressed by an optimization approach. There have been several studies exploring maritime fleet operations through the lens of optimization modeling, primarily focusing on economic objectives such as cost minimization (*13*, *7*, *14*), but also environmental concerns such as emissions reduction (*15*) or alternative fuels (*5*, *16*). The SEAMAPS model is a typical example of integrated least-cost fleet optimization, considering techno-economic parameters and environmental concerns through different fuel types and general emissions taxes (*17*, *18*). The SEAMAPS model accounts for constraints like fuel availability, emissions and prices as well as fleet level constraints, including ship production. The driving constraint in the model is that the transport demand must be fulfilled with the ship fleet, with the lowest cost. Least-cost optimization models have become integral to decarbonization efforts across various sectors, particularly in energy, where they facilitate the analysis and deployment of diverse technologies aimed at reducing greenhouse gas (GHG) emissions. Energy system optimization models (ESOMs) are widely utilized in cross sector decarbonization to evaluate the economic viability of integrating renewable energy sources, such as solar and wind, alongside traditional fossil fuels (*19*). These models enable stakeholders to explore a range of fuel and technology options while considering constraints like investment costs, operational efficiencies, and policy regulations. For instance, recent studies have employed capacity expansion models to identify optimal resource allocations that achieve net-zero emissions by 2050, emphasizing the need for technological flexibility and innovative solutions (*20*). Similarly, least-cost optimization has been applied to assess the implementation of carbon capture and storage (CCS) technologies, biomass utilization, and electrification strategies (*21*). By integrating techno-economic analysis with process modeling, these approaches provide a comprehensive understanding of the costs and benefits associated with various decarbonization pathways. Advancements in decision support systems and multi-criteria decision analysis further enhance the capability of sophisticated models to navigate complex trade-offs between economic performance and environmental impacts.

Yet, decarbonizing the maritime operations requires not just complying with these lowest-cost approaches but also a closer look at policy structures, operational steps, and infrastructure issues that condition the sector's capacity to transition to lower-carbon fuels. To elaborate more on these complexities, we rely on recent studies that investigate both the policy and technological dimensions of maritime decarbonization. The challenge of shipping decarbonization is highlighted by the interaction between operational procedures, technological development, and policy pressures (*22*). Recent techno-economic literature highlights that even increasingly efficient ship design and slow steaming will go a long way towards cutting emissions, but decarbonization of shipping would involve disruptive propulsion and fueling infrastructure innovation (*23*). In fact, only operational actions would reduce even a part of the industry's forecasted emissions, calling for the swift uptake of cleaner fuels such as ammonia, hydrogen, and next-generation biofuels (*22*). With respect to the fuels, a significant body of literature only focuses on alternative fuels. In this regard, real-options analysis has been also used to value investment in cleaner fuels (e.g., liquified natural gas (LNG) and other emission-reducing technologies) (*20*). In addition, the integration of environmental upgrading into global maritime value chains has been examined regarding ports' strategic role (*24*). Ports play the role of enablers of cleaner fuels and more sophisticated technological retrofitting, yet their performance is limited by the policy context and the ability of stakeholders to achieve a consensus on long-term decarbonization targets. This is coupled with demands for stakeholder alignment by both regulators and the industry for aligning shipping decarbonization trajectories with port infrastructure planning (*24*). Also coming to the forefront is the decision-support dimension. Acciaro demonstrates the way real-option valuation models may inform shipowners dealing with uncertainty regarding fuel price volatility and carbon fees, the need for flexible and adaptive models (*24*).

In this research, we combine insights from the literature on the means towards decarbonization, exploring a joint implementation of emission-reduction technologies, transition to cleaner fuels, under real policy frameworks, using a decision support system, the MaritimeGCH model. The MaritimeGCH model reflects this combinatory approach, making scenario-based projections involving policy-constrained inputs (e.g., ETS) in addition to technical parameters (fuel consumption, ship lifetimes) (*25*). Simulating policy shocks – e.g., how excess emissions penalties and allowances – can provide thresholds at which cleaner fuels become economic, providing insightful trade-offs. Finally, sustainable shipping has been extended to cover social and governance aspects, including stakeholder equity and working conditions (*24*). Although these factors are outside the direct scope of techno-economic models, they represent a new feature of maritime decarbonization literature. Collectively, these works highlight the worth of synergistic, dynamic, and policy-oriented modeling efforts toward more evolved decision-support systems with which to inform maritime stakeholders – especially in large shipping countries like Greece. And this is the gap this research tries to fill.

The MaritimeGCH model has been developed by the Global Climate Hub (GCH), an international research-led initiative under the United Nations Sustainable Development Solutions

Network (UN SDSN), aiming to provide climate-neutral and long-term sustainable pathways (*26*). The model guides investment decisions towards more sustainable shipping. It aims to minimize the cost imposed on a shipping fleet given constraints such as shipping demand, fuel availability and ship production capacity. The scenario evaluated projected moderate increases in shipping demand, fuel cost trajectories, and a gradual transition to cleaner fuels commiserate in the literature along with a combination of technologies implemented to increase the fuel efficiency of ships, and subsequently reduce their emissions.

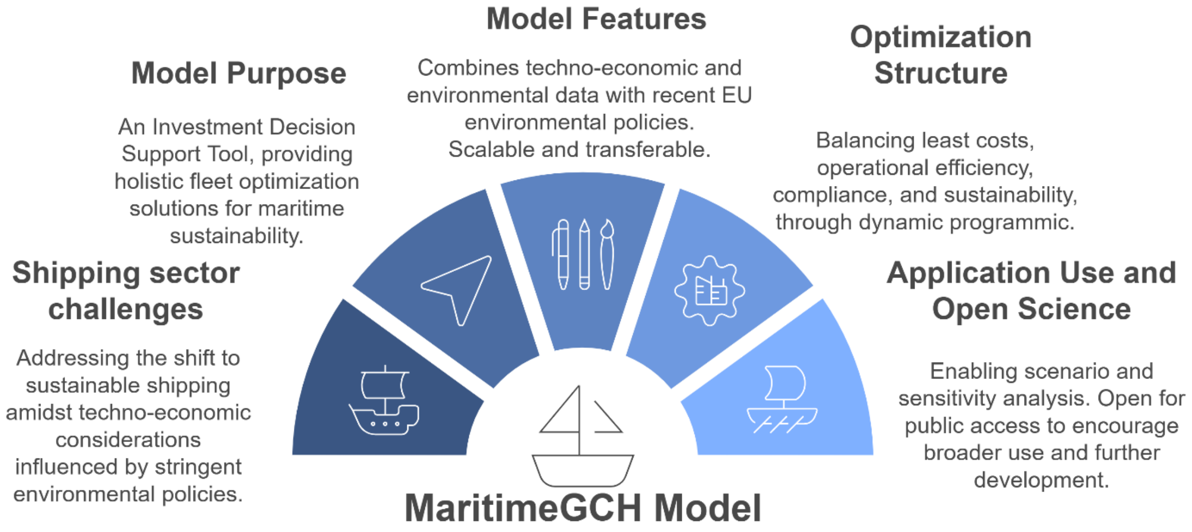

Figure 1. MaritimeGCH Overview. A schematic overview of the MaritimeGCH approach.

The MaritimeGCH model is a novel application in its holistic nature, as it combines economic, environmental, and ship-technical factors, incorporating recent European policies such as the CII and the ETS, while also considering greener shipping through alternative fuel types. Another advantage of this approach is that the MaritimeGCH model has been developed in Python language, making it accessible and freely available, based on an open-source code, allowing for modifications and improvements, and being also flexible in terms of input data, study scales, and scenarios exploration. To our knowledge, there is no similar application, and specifically for the Greek fleet, as for the first time it incorporates recent IMO and EU policy evaluation within an integrated techno-economic optimization framework.

Results

The MaritimeGCH model was applied to all ships under the Greek flag considering fuel consumption, shipping demand, operational, fuel, and investment costs, implemented efficiency technologies, and emissions cap specified by the FuelEU cap. The shipping demand was based on the SSP2 scenario, assuming steady economic growth and moderate population increases, with shipping demand rising steadily due to global trade expansion. Costs, efficiency gains from technology, and fuel consumption are based on current literature. Based on data from OECD, Greece emitted 87 $MtCO_2e$ in 2022, and based on data from Clarksons, the Greek fleet in its current composition is estimated to currently emit 103 $MtCO_2e$ in 2025 (*27*). In the model, we apply a decarbonization scenario, considering two main interventions: one is the implementation of a combination of technologies to increase fuel efficiency (on-ship emission-reduction technologies, a consumption-side measure) and the other is the transition to cleaner fuels over the 25-year time horizon from 2025-2050 (a supply-side measure). The supply side transition to new fuels assumes a gradual phase out of refined petroleum oil and marine oil with LNG and LPG (liquified petroleum gas) serving as a bridge to longer-term fuels such as methanol, ammonia, and hydrogen. As highlighted in Figure 1, the approach for the model is to provide holistic fleet optimization solutions to address the challenges in the shipping sector to integrate new technologies in a cost-efficient manner while adhering to stringent environmental policies. By enabling scenario and sensitivity analysis the tool encourages further development to incorporate increasingly complex features and interaction among relevant variables. For more details on the scenarios, please refer to the materials and methods section, and the Supplementary Material (SI).

The results for the decarbonization scenario show the fleet evolution, investment, and operational metrics until 2050, as well as the excess emissions according to the ETS regulation, with their associate penalty costs (Figure 2). As assumed, there is a steady growth in the shipping demand services according to the SSP2 projection, following a respective increase in the number of vessels for its coverage (slightly higher than 1,400 vessels by 2050). There is a notable increase in container (C) ships and a significant uptick in 'other' (O – mainly passenger) ships towards 2050. The investment costs remain relatively stable from 2020 to 2045 (fluctuating between €1,000 million and €1,500 million until 2045), followed by a marked increase approaching 2050, following the need for new vessels (nearly €2,000 million). The fuel demand distribution shows a declining reliance on oil as cleaner fuels gain prominence, indicating a strategic shift towards sustainability. Oil fuels give their place gradually to LNG and LPG in the mid-term, and NH_3, MeOH and H_2 in the long-term. With the combination of efficiency measures and technologies implemented, emissions are well below the cap set by the ETS and gradually increase as further shipping demand is met with fossil fuels. The results indicate an inflexion point in the mid-2040s as cleaner fuels displace fossil fuels and emissions monotonically begin to drop. This increases fuel costs significantly, as much as quadruples the cost compared to 2025. Simultaneously, emissions rising emissions until clean fuels come online coupled with a decreasing emissions cap impose costly ETS penalties on the fleet. By 2050, emissions reach approximately 65MTpa, 25MT above the cap, but trending in the right direction. This indicates that as soon as significant bunkering capabilities are going online within the next 20 years for cleaner fuels, emissions will significantly decrease by 2050 but increase in the short-term, in conjunction with fuel costs, doubly hurting the shipowners' bottom line when the ETS cap is exceeded.

The ETS cap on CO_2 emissions is based on the FuelEU standards, which aim to start at a 2% reduction in of emissions 2025, increasing to 6% in 2030, and accelerating from 2035 to reach an 80% reduction by 2050 (*28*). The cap is structured by the regulation to drive further incentives for decarbonization as solutions become more available and cost effective in the future. Accordingly, in the case of the Greek fleet, since limited solutions have been implemented through early 2025, the ETS cap modeled is structured to moderately decrease by 0.4% per year until 2030, and then linearly decreases by 1% per year until 2040, before accelerating its reduction until 2050.

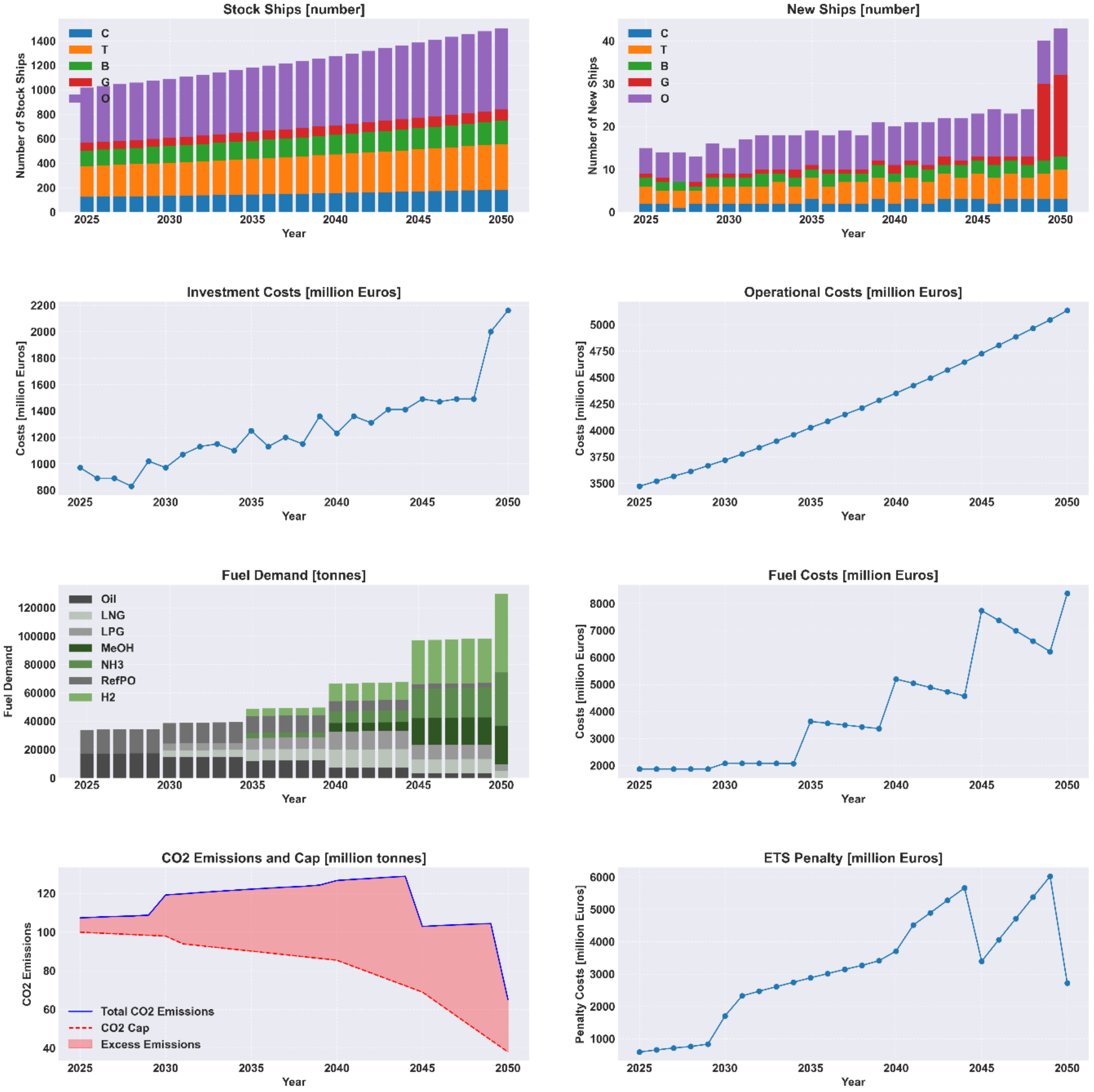

Figure 2. Results of the application to the Greek fleet. Shown is the base case with the combined technology scenario applied with a transition to cleaner fuels, including: the fleet composition (stock and new ships); investment and operational costs; fuel demand and the associated costs; the CO_2 emissions compared to the ETS threshold, and the associated penalty.

We have run also a sensitivity analysis to report each relevant parameter's effect on total costs, and emissions. The parameters involved were ETS, fuel consumption and cost, and demand for shipping services. For the ETS, we tested an optimistic case that sees 5% or more reduction in emissions per year and a pessimistic case that sees little acceleration in reductions from 2040-2050, unlike the base case. As described in the materials and methods section and supplementary information, shipping demand was based on a middle-moderate condition that assumes moderate growth in demand, following the second shared socioeconomic pathway (SSP2). Here we explore two other 'extreme' cases: first an SSP1 situation – a pathway assuming a rapid shift towards sustainability, and second, an SSP5 situation, expressing an unsustainable pathway that assumes accelerated demand into the mid-century. Cost and fuel consumption sensitivities used figures from existing literature, as described in the materials and methods section, and were tested over their potentially minimum and maximum values.

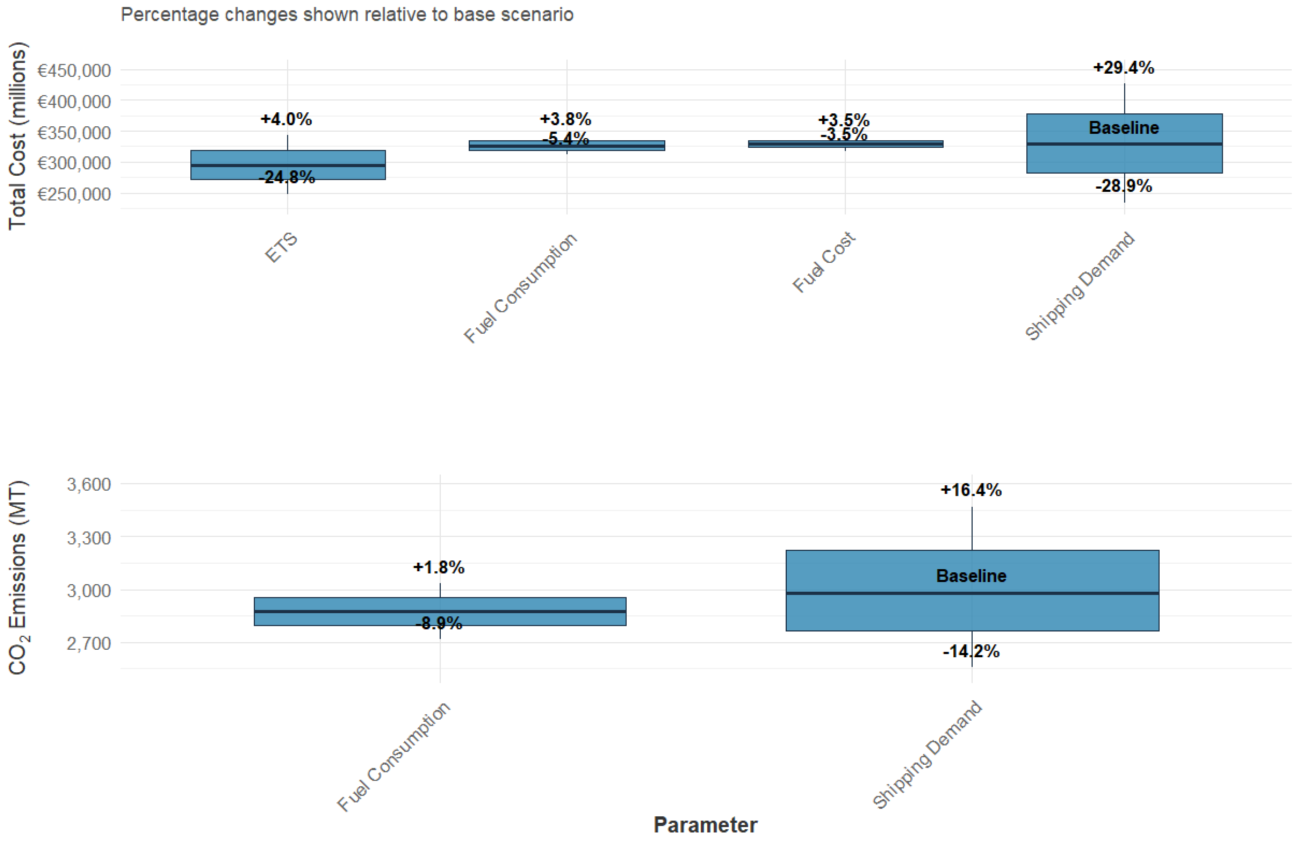

Figure 3: Sensitivity analysis. Range of total emissions for scenarios testing the sensitivity of each variable. Shipping demand, predictably, has the largest effect on emissions. A faster transition to cleaner fuels decreases total emissions by 11.2% compared to the baseline

Figure 3 shows the range of emissions and costs for the entire fleet given the range of input values of each variable for the sensitivity analysis (x-axis). The results show that overall shipping demand is the main driver of the fleet's emissions, with the difference in emissions in 2050 between the high-growth scenario and low-growth scenario being 14.2-16.4%. A slower transition to cleaner fuels results in a small uptick in emissions due to increasing demand while a fast transition to cleaner fuels can decrease emissions by 9.9% in 2050. In terms of total costs, again the demand in shipping services is the more influential parameter, as it primarily shapes the fleet size and composition, which in turn define its investment and operational costs. It seems that shipping demand can increase or decrease investment and operational costs by around 29%. The effect of ETS follows, as the emissions exceeding the cap consist a significant 'external' cost. It seems that the ETS prices can affect fleet costs up to 25%. This is an important consideration for policymakers as shipowners start to contend with emissions caps. Unsurprisingly, fuel consumption and costs do not play a large role in the overall cost for the fleet, indicating the potential techno-economic (consumption based, and market based) adaptations in order to cover the demand.

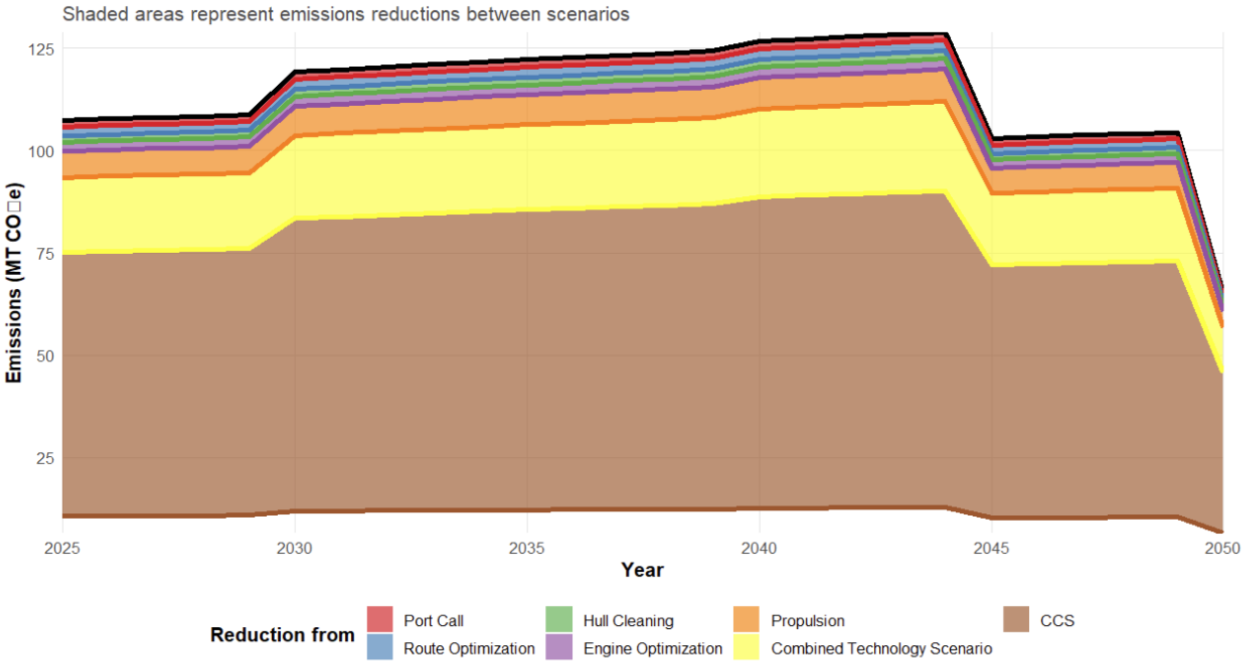

Figure 4: Emissions reduction by on-ship emission-reduction technology. CCS has the largest impact on emissions, followed by the combined efficiency scenario. Individually, propulsion technology has the largest potential to reduce emissions through efficiency, while the effects of port call, route optimization and hull cleaning have marginal separate impacts.

Figure 4 shows the marginal emissions reductions for each emission-reduction technology implemented individually and the combined efficiency technology scenario. Besides CCS, which is still in the early stages of development, new propulsion technology has the largest stand-alone emissions reduction. The combined technology scenario achieves a 25% reduction in emissions compared to a do-nothing scenario (e.g. current emissions), emphasizing the need to coordinate the implementation of both physical and digital efficiency technologies. Port call, hull cleaning, and route optimization achieve fewer comparative effects on emissions.

Based on these findings, it can be concluded that without further action in terms of subsidies, technological advancement or accelerated clean fuel, and serious commitments, the full decarbonization of the maritime industry by 2050 is not possible. However, shipowners can reduce emissions and align the economic incentive to reduce ETS penalties if mature technologies can be implemented immediately and in combination with one another.

Discussion

The Maritime GCH model application has provided an integrated picture of the maritime operations, and the evaluation of different strategies. This is an insightful approach for shipowners' decisions on how to meet shipping demand, subject to practical techno-economic and environmental constraints. Such integrated model-based investment decision support tools should be further adopted to provide solutions weighing the costs and benefits of decarbonization efforts.

The model is not without limitations, referring to the necessary assumptions to run such a system-wide application. The relationships between input data is complex and their effect on one another in this study is linear. Ship types, fuel efficiencies and costs, and ship operating and investment costs are assumed to follow linearly to projected values in the future. Further refining such assumptions and data interrelations (e.g. feedback loops) are currently the subject of future work within the model. Such modifications would make the model non-linear, making it significantly more complex and computationally demanding, so are beyond the scope of the present research, which was to provide a first overview of what it might take to decarbonize a large fleet. The sensitivity analyses performed serve to account for any uncertainties. As mentioned, the scope here was to provide a holistic picture of an important shipping industry in view of existing techno-economic and new environmental challenges, under potential decarbonization scenarios. This goal was met, as the results provide critical insights into the need for coordinated and timely efforts towards green shipping.

We show that even with aggressive fuel transition in the mid-late 2030s considering a full efficiency technology adoption, reducing fuel consumption significantly and reducing emissions below the cap proposed by the ETS, the fleet's decarbonization will be extremely difficult, if not impossible, to achieve. According to our analysis, while emissions do decline near the cap, ETS penalties are still imposed. As shown in the sensitivity analysis, this is largely due to the increased shipping demand expected in the sector, which also increases costs the most (besides the ETS penalties) for shipowners.

Despite the 2024 EU ETS inclusion of maritime transport, shipping – one of the economic pillars of Greece – remains lacking a national climate strategy, as of early 2025. The danger of omitting maritime decarbonization from national energy planning is increasing ETS expenses and operating discontinuity for shipowners. The overall slow progress so far achieves the NECP targets (and Greek national commitments) quite challenging, as documented by the European Environment Agency (EEA) and echoed in recent analyses (e.g., IEA reports and the NECP review by the European Commission) (*29*). Moreover, our decarbonization scenario is quite optimistic in purpose, imposing a joint adoption of multiple emissions-reduction technologies, and cleaner fuels. These require a behavioral change in the adoption of such technologies, which might even not be adopted all together, as well as the use of cleaner fuels in ports internationally, not just in Greece. So curbing emissions is even more challenging, and subject to international commitment and cooperation.

Notwithstanding the inclusion of a series of technological interventions and cleaner fuel transitions, our models reveal an unavoidable disparity between the achieved emissions pathway and ambitious 2050 decarbonization ambitions. This concurs with recent literature (Franz & Bramstoft, 2024) recognizing that in the absence of enabling policy support (e.g., zero-carbon fuel tax credits or subsidy on upfront retrofitting technology), the industry could be exposed to rising ETS expenses, eroding competitiveness.

As the shipping industry confronts increasingly stringent global emissions regulations and mounting pressure to transition to low-carbon technologies, tools like these become essential actions for timely decarbonization. While full decarbonization is shown to be quite difficult, joint action by researchers, shipowners and policymakers is recommended, as several transitions must occur in parallel: the technology, fuel production and long-term ship investment are needed to achieve decarbonization, each requiring action by the private and public sector as well as the global policy within the industry.

Research on this subject can be accelerated by key data becoming freely available. One of the main challenges of this study was the acquisition of integrated data. Currently, data is confidential or behind paywalls, making it hard for researchers to analyze the provide solutions grounded in the realities of the shipping industry. Shipowners should start evaluating which mature technologies they can begin integrating into their operations. The Greek government should not delay any further in aligning its strategy for growth with the guidelines set by the IMO. This would align one of the country's largest and culturally important industries with its national policy. Additionally, policymakers should work to provide incentives for shipowners to coordinate regarding clean fuel purchases and new ship investments to ensure fleet-wide actions are taken, and not just by individual shipowners. This will also drive the necessary technology-readiness up to the necessary pace. Furthermore, international cooperation for the adoption of cleaner fuels is of paramount importance to curb emissions. In view of the planning horizon of this analysis, it might be likely that international and European decarbonization targets will need more time to be achieved. Greek policymakers are urged to pursue a twin track: (a) expediting port infrastructure planning to receive fuels such as hydrogen and ammonia, and (b) introducing targeted carbon pricing incentives or technology funds that encourage early adoption. Non-compliance not only risks ETS non-compliance but also foregone green maritime leadership opportunities, considering Greece's traditional frontier role in global shipping.

Materials and Methods

The MaritimeGCH model is an Investment Decision Support Tool (IDST) developed by the GCH. It is based on optimization, mathematically describing the examined problem, and solving it while satisfying many (often conflicting) objectives (*30*). The model uses dynamic linear programming (LP) to minimize the total cost of fleet operations over a user-defined planning horizon (in this case 2020-2050). It includes decision variables (e.g., fleet composition, fuel choices), the objective function (e.g., minimizing total cost), and constraints (e.g., similar to the aforementioned regulations or emissions caps, shipping demand, technological limitations, etc.) (Table 1).

The objective function of the model is to minimize the total cost for all ships travelling under the Greek flag, over the planning horizon, as shown in Equations 1 and 2 below:

$$min \sum_{y=2020}^{2050} \left(total\_cost_y\right) \text{ Total cost in year y (in million Euros)} \quad (1)$$

Such that total cost is:

$$total\_cost_y = \sum_s \left(new\_ship_{y,s} \times invest\_cost_s\right) + \sum_s \left(stock\_ship_{y,s} \times op\_cost_s\right) + \sum_s \left(fuel\_demand_{y,f} \times fuel\_cost_f\right) + \left(excess\_emissions_y \times ETS\_price_y\right) \quad (2)$$

The variables used are described in further detail in Table 1 below. The model's constraints are:

- Fleet Capacity Constraint (Equation 3): The total stock of ships each year must be sufficient to meet the demand for shipping services. The shipping demand was considered according to different future projections according to the Shared Socioeconomic Pathways (SSPs). The SSP2 demand projection was used in the model, while other cases (e.g. SSP1, SSP5, etc.) were considered for sensitivity analysis.

$$\sum_s \left(stock\_ship_{y,s} \times cap_s\right) \geq demand\_shipping_y \quad \forall y \quad (3)$$

- Ship Production Constraint (Equation 4): The number of new ships built each year is limited by production capacity:

$$new\_ship_{y,s} \leq prod\_capacity_{y,s} \quad \forall y, s \quad (4)$$

- Fleet Stock Update Constraint (Equations 5-8): The stock of ships of each type in a given year is the sum of new ships built and surviving ships from previous years, based on their lifetime and age:

$$\text{If y=2020, } stock\_ship_{y,s} = init\_capacity\_fleet_s \quad (5)$$

Else: $stock_{ship_{y,s}} = new_{ship_{y,s}} + stock_{ship_{y-1,s}} - retired_{ships_{y,s}} \quad \forall\, y, s > 2020$ (6)

Where: $retired_{ships_{y,s}} = \sum_{y,}\ new\_ship_{y\prime,s}$ (7)

for y’ ∈ [max (2020, y - lifetime[s] + 1 - fleet_age[s]), y-1] (8)

- Fuel Demand and Availability Constraints (Equations 9,10): The fuel demand is derived from the operational needs of the ships, which, however, cannot exceed the available amount of each fuel type this year:

$fuel\_demand_{y,f} = \sum_{s,eng}\ stock\_ship_{y,s} \times fuel\_consumption_{s,f,eng} \quad \forall\, y, f, s, eng$ (9)

And $fuel\_demand_{y,f} \leq fuel\_avail_{f,y}\ \forall\, y, f$ (10)

- Emissions Estimation (Equation 11): The total CO_2 emissions are calculated based on fuels consumption:

$co2\_emissions_y = \sum_f\ fuel\_demand_{y,f} \times emissions\_factor_f \quad \forall y$ (11)

- ETS Emissions Cap Constraint (Equations 12,13): The total CO_2 emissions in each year must not exceed the threshold (cap) plus any excess emissions (which will have to be then purchased):

$co2\_emissions_y \leq co2\_cap_y + excess\_emissions_y \quad \forall y$ (12)

And $excess\_emissions_y \geq 0 \quad \forall y$ (13)

With this approach we set a CO_2 emissions cap, allowing its exceedance, but any excess is tracked, and ‘penalized’ with an additional cost in the objective function. This is a ‘combined’ approach (threshold-constraint and penalty), and it is realistic and effective, as it mirrors simply the actual ETS regulatory environment where companies can exceed their caps by purchasing allowances (*31*).

- Carbon Intensity Indicator Constraint (Equations 14,15): It should not exceed a performance defined by regulations, or the user/ owner ($CII_{desired\ per\ ship\ type\ s}$) in order to ensure that the ship will remain in the ‘active’ fleet:

$CII_{s,y} \leq CII_{desired,s}$ (14)

The $CII_{desired,s}$ is equivalent approach to the AER, as they are based on almost the same equation and concept, to set an environmental standard/grading to allow ships to travel. For example, in this constraint it can be reflected by setting the $CII_{desired,s}$ equal to the respective grade “C” (AER class) or better (B or A grade), because the regulation implies the ships not to travel if they are graded D (for three consecutive years) or below (*3*). Where: $CII_{s,y}$ is the Carbon Intensity Indicator of ship type s per year is estimated as:

$CII_{s,y} = \frac{co2\_emissions_y}{cap_s}$ (15)

Table 1: Model components. Sets and indices, parameters and decision variables used in the model

Category	Symbol	Description	Domain/Units
Sets and Indices			
Years	y	Planning horizon	$y \in \{2020, \ldots, 2050\}$
Ship Types	s	Ship categories	$s \in$ {Cargo, Tanker, Bulk, General, Other}
Fuel Types	f	Fuel options	$s \in$ {Oil, LNG, LPG, MeOH, NH3, CH4}
Parameters			
Investment Costs	$invest\_cost_s$	Ship investment cost	Million Euros
Operational Costs	op_cost_s	Annual operational cost	Million Euros/year
Fuel Costs	$fuel\_cost_f$	Fuel cost	Euros/tonne
Emissions Factor	$emissions\_factors_f$	CO2 emissions per fuel	Tonnes CO_2/tonne
CO_2 Emissions Cap	$CO2\_cap_y$	Annual CO2 threshold	Tonnes CO_2
ETS Price	ETS_price_y	Excess emissions costs	Euros/tonne CO_2
Production Capacity	$prod\_capacity_{y,s}$	Max ships producible	Number of ships
Ship Lifetime	$lifetime_s$	Ship operational duration	Years
Fuel Consumption	$fuel\_consumption_{s,f,eng}$	Fuel usage per ship	Tonnes fuel/year
Shipping Demand	$demand\_shipping_{y,s}$	Required shipping service	Gross Tonnage/Nautical Mile
Initial Fleet Capacity	$init\_capacity\_fleet_s$	Initial ship count	Number of ships
Fleet Initial Age	$fleet\_age_s$	Initial fleet average age	Years
Fuel Availability	$fuel\_avail_{f,y}$	Fuel quantity available	Tonnes
Ship Capacity	cap_s	Initial ship count	Gross Tonnage/Nautical Mile
Desired CII	$CII\_desired_s$	Target intensity indicator	Dimensionless
Decision Variables			
New Ships	$new\_ship_{y,s}$	Ships s built in year y	Number of ships
Ship Stock	$stock\_ship_{y,s}$	Total ships s in year y	Number of ships
Fuel Demand	$fuel\_demand_{f,y}$	Fuel consumption f in year y	Tonnes
CO_2 Emissions	$CO2\_emissions_y$	Total annual emissions in year y	Tonnes CO_2
Excess Emissions	$excess\_emissions_y$	Emissions above cap in year y	Tonnes CO_2

So, the model achieves an optimization of new vessels, along with their fuel consumption and CO_2 emissions while adhering to operational and environmental constraints, according to the existing European policies.

The data and the parameters outlined in Table 1, were collected from a mix of datasets, including Clarksons Research, UNCTAD, MarineTraffic and information from legal frameworks such as FuelEU as well as the ETS and information from legal frameworks like FuelEU. We cross-validated our starting point values (fleet size, fuel mix, operating costs) against 2015–2020 Clarksons and MarineTraffic data. Possible future extensions to the model include introducing non-linear interactions between fuel and bunkering availability, and feedback on well-to-wake emission multipliers. These complications introduce realism at the expense of computability—a challenge under active research in state-of-the-art maritime decision support.

We examine the potential for shipping decarbonization through a scenario combining two primary interventions, in line with the recent European policies: adoption of emissions reduction technologies, and transition to cleaner fuels (*32*) ; (*33*)). In particular, the following emissions reduction technologies were considered, jointly:

- Engine power optimization: tuning engines for efficiency, potentially using advanced fuel injection systems, and optimizing speed for reduced fuel consumption and emissions (*34*)
- Route Optimizer technology: real-time weather and sea conditions to determine the most fuel-efficient and emissions-saving routes (*14*)
- Port-call technology for optimal entrance to a port: streamline vessel arrival times to ports, reducing idle time, fuel consumption, and emissions during waiting periods (*24*)
- Propulsion system improvements: more efficient systems, such as wind-assisted propulsion, air lubrication systems, or fuel use efficiency improvements (*35*, *36*)
- Hull cleaning and maintenance: technologies to clean the ship aiming at reduced traction, and subsequently emissions (*37*, *38*)
- On-board post-combustion carbon capture at 90% capture rate (*39*)

This set of technologies has a certain emissions reduction potential, which is reflected in their respective fuel consumption variable, and comes at the expense of higher operational costs.

The second intervention refers to the transition to cleaner fuels. We evaluate distinct scenarios of a slow, medium and fast transition to cleaner fuels by 2050. A moderate transition scenario to cleaner fuels was used as the average case, assuming oil-type fuels phasing out (oil and RefOil), being replaced by transition gas-type fuels initially (LNG and NPG), while green fuels (MeOH, NH_3 and H_2) ultimately becoming more prevalent in the future. Fuel costs are derived using today's prices, and projections are based on the DNV Maritime fuel price projections. Low, average and high price scenarios are considered by 2050.

Sensitivity analysis was performed for all model's variables, including shipping demand, fuel cost, fuel consumption, ETS prices, and emissions caps, considering a range of potential outcomes. Further information on these scenarios can be found in the SI.

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