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Applying the MaritimeGCH model for Greek shipping and its relevance to the Sustainable Development Goals (SDGs)

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Abstract

The maritime sector faces multiple techno-economic, environmental and development challenges, requiring careful investment decisions. Several of these challenges and factors are related to the Sustainable Development Goals (SDGs). The need for holistic solutions that can address these considerations simultaneously is becoming increasingly pressing. In this chapter we present the application of a free, open-source Investment Decision Support Tool, called MaritimeGCH, to the Greek fleet as a case study example. The model aims to optimize the fleet composition (based on the minimization of the total costs) under techno-economic, environmental, operational factors and European environmental regulations. After the model description, a presentation on its application, directly and indirectly relevant to various SDGs, including: cleaner fuel mixes (SDG7 on Energy), new ships and technologies (SDG9 on Industry), policies for more environmental-friendly shipping (SDG13 on Climate Action and SDG14 on life below water), and meeting shipping demands (SDG8 on Economic Growth).

Keywords: MaritimeGCH; Fleet Optimization; Shipping; Sustainable Development Goals; Greece.

1. Introduction: Towards sustainable shipping

Challenges of the maritime industry, including stricter environmental regulations with the urgent need to reduce greenhouse gases (GHG) emissions, economic goals, increasing needs and demand for shipping services, amidst the transition to greener fuels.

The IMO and EU have developed a regulatory framework that is aimed at substantially reducing GHG emissions generated by ships through ambitious milestones toward 2030 and 2040. The IMO, in its 2023 Revised GHG Strategy, has so far proposed the following reductions of GHG emissions: by 2030, with a minimum of a 20% reduction; and by 2040, at least a 70% reduction, both relative to 2008 levels, including at least 5% uptake of zero or near-zero GHG emission technologies no later than 2030 (IMO, 2023)

Annual GHG emission estimates by the IMO are to be done on the outcome basis, by applying the Carbon Intensity Indicator (CII) and the Energy Efficiency Existing Ship Index (EEXI). The CII and the EEXI introduced by the IMO mandate that ships assess their energy efficiency and operational carbon intensity, respectively, with performance ratings ranging from A to E (IMO, 2021).

The adoption was done in 2021, with effectiveness starting from January 2023. According to Faber et al. (2020), CII aims to control and measure carbon intensity of ships, that is, grams of CO2 emitted per unit of transport work. The annual CII is based on the data of IMO DCS, and a ship is graded between A and E. If a ship scores a D grade for three successive years or an E grade in a single year, a corrective action plan must be submitted as part of the SEEMP. Among the most important schemes to be finalized and implemented by the International Maritime Organization so far for improving measurement and reporting of GHG emissions by ships is the IMO Data Collection System. The DCS, which came into effect in 2019, IMO 2019, requires ships of 5,000 gross tonnage and above to collect and report data on fuel consumption that is then used to estimate total annual GHG emissions.

AER and capacity gross ton distance (cgDist) are CIIs for monitoring emissions in the cargo segments. AER will be applied on weight-critical segments and on volume-critical cargo supported with data from the IMO DCS system. Its use started with the early 2010s, part of the Energy Efficiency Design Index framework, according to which EEDI would be adopted and applied (IMO, 2016; Johnson et al., 2013). AER then benchmarks ships against efficiency standards to identify areas of improvement that could be made, such as route optimization, speed, and other operational practices that will reduce emissions.

The ETS-European Trading System was launched in 2005 under Regulation (EU) 2003/87 of 2003, which, according to EU Climate Action, has been designed for GHG emission reductions by placing a cap on particular emissions. These include sectors such as power and manufacturing but also maritime transport since January 2024.

Complementing these efforts, the EU has extended its ETS to maritime transport, requiring large vessels to monitor and report CO2 emissions and purchase emission allowances for compliance under an overall goal of a 40% reduction in shipping emissions by 2030 (European Commission, 2023). The ETS aims to reduce GHG emissions by setting a cap on the total amount of certain GHGs that can be emitted by installations covered by the system (European Commission, 2021; Psaraftis, 2019).

The FuelEU Maritime (Regulation (EU) 2023/1805, 2023) further requires ships over 5,000 gross tonnage to monitor GHG intensity, imposing a 2% reduction by 2025, escalating to 6% by 2030, and ultimately targeting an 80% reduction by 2050. This emphasizes renewable and low-carbon fuels, with fuel standards calculated on a well-to-wake basis to ensure comprehensive accounting of emissions. Additionally, under the EU MRV regulation (Regulation (EU) 2015/757, 2015), ships above 5,000 GT must report their CO_2 emissions on a yearly basis; changes in 2023 extended this to methane (CH_4) and nitrous oxide (N_2O) reporting starting in 2024. The EU MRV, forms an essential component in the development of the maritime transport sector's contribution to environmental policy and facilitates the implementation of the EU ETS and FuelEU Maritime.

The IMO DCS and EU MRV systems together provide a full approach to tracking maritime emissions, which enables informed decisions to be made in furthering the transition of shipping to more sustainable practices.

The above is to create a net incentive for shipping operators to switch to cleaner fuels and make the sector more efficient in support of broader EU climate targets of a 55% net GHG reduction by 2030 and climate neutrality by 2050, as part of the Fit for 55 package. Meanwhile, The Alternative Fuels Infrastructure Regulation, (Regulation (EU) 2023/1804, 2023) applicable as of April 13, 2024, is an important part of the Fit for 55 package that the EU has put forward to enhance the deployment of alternative fuels infrastructure across all modes of transport. This Regulation replaces the earlier Directive 2014/94/EU and lays down specific objectives so that all EU Member States will be able to develop the relevant infrastructure to support the market uptake of alternative fuel vehicles, thus contributing to the EU's climate goals. These create one big holistic step toward the goals of sustainability in shipping.

By integrating such complementary frameworks into the existing policy inventory, including IMO DCS, EU MRV, FuelEU Maritime, and many others, the actors will be able to make a far more coherent drive toward sustainability in maritime transport while successfully responding to climate change challenges. (Nisiforou et al., 2022; Handl, 2023; Koilo, 2024).

Besides what has been mentioned, some other complementary frameworks and strategies complement the above. The IMO's strategies go in tune with the call by the Paris Agreement to keep global warming below an increase of 2 degrees Celsius as much as possible. Shipping accounts for a lot in contributing to reduction commitments enlisted in this agreement. In addition, the Sustainable Development Goals (SDGs) (United Nations) instituted by the United Nations within the 2030 Agenda, provide a holistic framework to tackle global issues such as climate change, economic disparity, and environmental deterioration. The initiatives of IMO and EU cater to a number of SDGs, majorly Goal 13, Climate Action, and Goal 14, Life Below Water. By helping in the sustainable development of shipping, these policies support broader global efforts toward sustainability.

As a response to the need for more holistic and sophisticated approaches to address the increasing considerations of the maritime industry, the Global Climate Hub (GCH) initiative is committed in providing scientific solutions and models. Under the UN’s Sustainable Development Solutions Network (SDSN, 2022), we developed the GCH (SDSN, 2024), an international research-led initiative (Alamanos, 2024; Koundouri et al., 2024), hosted by Athens University of Economics and Business (AUEB) and the “Athena” Research and Innovation Center. The MaritimeGCH model was designed by the GCH, to assist addressing complex challenges of the maritime sector and making it more sustainable.

In this chapter we present an application of the MaritimeGCH model for the Greek fleet, aiming to both efficient and cost-minimizing investments, as well as improvement of several SDGs.

2. Materials and Methods

2.1 A brief description of the Greek shipping sector

Greek shipping predominates the worldwide maritime industry. It is considered a powerhouse in worldwide shipping but more so by cargo-carrying capacity. The Greek-owned fleet, for its part, was still the leading one in shipping as of January 1, 2024. The Greek-owned fleet comprises 3,428 ships, enjoying a total capacity of 394.97 million deadweight tons. This includes 23.6% of the global tanker fleet and 17.2% of dry bulk carriers. Regarding the national flag fleet, Greece has 1,214 propelled seagoing merchant vessels of 100 gross tons (GT) and above, amounting to 58.94 million DWT. This represents approximately 2.588% of the total world merchant fleet. (UNCTAD, 2023/2024.)

These statistics underscore Greece's pivotal role in international shipping, both through its nationally flagged vessels and its globally owned fleet. (UNCTAD, 2023/2024.)

The report also makes it clear that there is fierce competition from Asian fleets, while Greece remains the biggest worldwide in terms of transport capacity and total value. The Chinese fleet comes second, with 309.8 million dwt, or 13.3% of global tonnage, and 11.6% of its commercial value.

Thus, while China may be at the top in gross tonnage, Greece is still considered to be in the leading positions by cargo capacity and certain market segments.

This significance arises from a longstanding heritage of nautical proficiency and a strategic emphasis on international shipping markets, establishing it as a fundamental element of global commerce and economic stability (Alexandropoulou et al., 2021; Papandreou et al., 2021). Greek shipping enterprises manage a very varied fleet, encompassing tankers, bulk carriers, cargo vessels, and LNG carriers.

This elasticity allows Greece to meet with competence the various new demands of world shipping. The national fleet plays a very significant role in carrying energy resources, raw materials for industries, and finished consumer goods across the globe; it thus ensures chain supply.

There has been a gradual increase in the consideration of environmental activities within industry practice, as reflected in global decarbonization goals and the need for a reduction in emissions. The adoption of cleaner fuels and green technology-foreign going LNG-powered boats, including energy-efficient retrofits-all falls within international policy actions such as the IMO 2050 goals (Nisiforou et al., 2022). Greek shipping has actively involved itself in various current and ongoing projects, highlighting their commitment toward aligning business with environmental care (Alexandropoulou et al., 2021).

Greek shipping is an essential part of the national economy, and it contributes much to the GDP, employment, and government revenues. Greece enjoys healthy trade, with merchandise trade amounting to $144.54 billion, comprising $55.07 billion in exports and $89.47 billion in imports. In 2023, the country recorded a GDP of $242.45 billion with a growth rate of 3.71%, while its transport services exports reached $22.71 billion, further underlining the dependency of its economy on maritime transport. In addition, Greek ports handled 5.17 million TEUs in container throughput, showcasing the nation's significant contribution to world shipping and trade logistics (UNCTAD, 2024).

Over and above the quantified importance of this fleet, Greece's very strong maritime tradition and dependence of its economy on shipping render this country a fundamental actor in this industry's movement toward sustainability. With leading roles in both implementing international maritime regulations and using advanced technologies, Greece is right in the middle of global decarbonization efforts that involve the shipping sector. Therefore, the scale, influence, and progressive actions of the country place it uniquely as a very interesting and relevant case study for the understanding of economic, environmental, and regulatory factors in modern shipping.

2.2 The MaritimeGCH optimization model

There have been several studies exploring maritime fleet operations through the lens of optimization modelling, primarily focusing on economic objectives such as cost minimization (Al-Enazi et al., 2022; Psaraftis et al., 2013; Meng et al., 2014), but also environmental concerns such as emissions reduction (Perčić et al., 2021) or alternative fuels (Faber et al., 2020; Johnson et al., 2013). The SEAMAPS model is another example of an integrated advanced least-cost fleet optimization approach, considering techno-economic parameters and environmental concerns through different fuel types and general emissions taxes (Franz et al., 2022; Franz and Bramstoft, 2024). The MaritimeGCH model is a novel application however, as it combines economic, environmental, and ship-technical factors while also incorporating recent European policies such as the CII and AER, and the ETS, while also considering greener shipping through alternative fuel types. Another comparative advantage is that it has been developed in Python language, making it accessible and freely available, based on an open-source code, allowing for modifications and improvements.

The MaritimeGCH model is an advanced optimization Investment Decision Support Tool (IDST). It is based on optimization, namely it describes mathematically the problem that we need to solve with the best possible way, satisfying many (often conflicting) objectives (Alamanos and Garcia, 2024). The model uses 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), objective function (e.g., minimizing total cost), and constraints (e.g., similar to the aforementioned regulations or emissions caps, shipping demand, technological limitations, etc.) (Han et al., 2023). The CII (and AER) and ETS regulations are also modeled as constraints. Table 1 provides an outline of the model's mathematical structure.

Table 1. The mathematical description of the MaritimeGCH model.

<u>**Sets and Indices**</u> ● **years:** Set of years, expressing the planning horizon, indexed by y. In this example, we assume this period to be from 2020 to 2050. ● **ship_types**: Set of ship types, indexed by s. These can be for instance: Container, Tanker, Bulk, Cargo, Other. ● **fuel_types**: Set of fuel types, indexed by f. These can include for example: Marine Fuel Oil or Heavy Fuel Oil (Oil), Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Methane (MET), Methanol (MeOH), Ammonia (NH_3), other alternative fuels except of LNG (AllNoLNG), refined petroleum oils (RefPO), Hydrogen (H_2), or other fuel blends allowing different mixes, which is often the case when ships refuel at different ports. ● **engine_types**: Set of engine types, indexed by eng, incuding: ME-C engine, ME-GI (high pressure gas engine), ME-LGI (liquid gas injection), or Multi-Fuel Engines (MFE).
<u>**Parameters** (the model's data or assumptions)</u> ● **invest_cost$_s$**: Investment cost of ship type s (in million Euros). ● **op_cost$_s$**: Operational cost of ship type s per year (in million Euros). ● **fuel_cost$_f$**: Fuel cost of fuel type f (in Euros per tonne). ● **emissions_factor$_f$**: Emission factor of fuel type f (tonnes of CO_2 per tonne of fuel).

- **co2_cap$_y$**: CO_2 emissions cap (threshold) in year y (tonnes of emitted CO_2). If the company exceeds that, then they will have to buy CO_2 emissions allowance (see next bullet), according to the ETS.
- **ETS_price$_y$**: Cost per tonne of CO_2 for emissions exceeding the cap in year y (Euros per tonne of CO_2).
- **prod_capacity$_{y,s}$**: Production capacity of ship type s in year y (number of ships that can be produced).
- **lifetime$_s$**: Lifetime of ship type s (in years).
- **fuel_consumption$_{s,f,eng}$**: Fuel consumption of ship type s using fuel type f (tonnes of fuel per year) per engine type eng.
- **demand_shipping$_{y,s}$**: Demand for shipping services in year y [Gross Tonnage per Nautical Mile (GtNM)] of ship type s in year y.
- **init_capacity_fleet**: Initial capacity of fleet of ship type s in the year 2020 (number of ships).
- **fleet_age**: the initial (average) age of the fleet, per ship type (years).
- **fuel_avail$_{f,y}$**: Available amount of fuel type f that can be used per year y (tonnes).
- **cap$_s$**: Capacity, namely the weight of each ship types' load (GtNM).
- $CII_{desired,s}$: Desired value of Carbon Intensity Indicator of ship type s (or equivalently the AER class).

<u>Decision Variables</u>

- **new_ship$_y$**: Number of new ships of type s in year y.
- **stock_ship$_y$**: Stock of ships of type s in year y.
- **fuel_demand$_{f,y}$**: Fuel demand of fuel type f in year y (tonnes).
- **co2_emissions$_y$**: CO_2 emissions in year y (tonnes of CO_2).
- **excess_emissions$_y$**: Excess CO_2 emissions above the cap in year y (tonnes of CO_2).

<u>**Objective Function** = Minimize the total cost over the planning horizon (e.g., 2020-2050)</u>:

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

Where:

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

<u>Constraints:</u>

Fleet Capacity Constraint: The total stock of ships each year must be sufficient to meet the demand for shipping services:

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

Ship Production Constraint: The number of new ships built each year is limited by production capacity:

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

Fleet Stock Update Constraint: 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:

If y=2020, $stock\_ship_{y,s} = init\_capacity\_fleet_s$ (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: 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 Constraint: The total CO_2 emissions are calculated based on fuel consumption:
$co2\_emissions_y = \sum_f \; fuel\_demand_{y,f} \times emissions\_factor_f \;\; \forall y$ (11)

ETS Emissions Cap Constraint: The total CO_2 emissions in each year must not exceed the cap threshold plus any excess emissions (which will have to be then purchased):
$co2\_emissions_y \leq co2\_cap_y + excess\_emissions_y \;\; \forall y$ (12)

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

With this approach we set a CO_2 emissions cap (threshold). B) We allow emissions to exceed this cap, 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 (European Commission, 2023; 2022).

Carbon Intensity Indicator Constraint: 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 actually the same/ equivalent approach as the AER, as they are based on almost the same equation and concept, to set an environmental standard 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 (IMO, 2022).

Where: $CII_{s,y}$ = Carbon Intensity Indicator of ship type s per year is estimated as (IMO, 2022):

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

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.

3. Results

The data mentioned above, as well as the parameters outlined in Table 1, were collected for various cases, reflecting different real-world situations. In order to run the model, the user needs to select the values of these parameters, or simply put, select a scenario. For the input data, we used a mix of datasets retrieved by Clarksons Research, 2023; UNCTAD, 2024; MarineTraffic, 2024; European Commission, 2024a, 2024b and representative values from the literature to the context of our problem. In this chapter, we demonstrate the MaritimeGCH model's application to the Greek fleet, choosing the following configuration:

We assume the average fuel costs (typical 'medium' case). We also selected a moderate transition to greener fuels, as a plausible projection to 2050. That would mean a gradual phase out of oil fuels (Oil and RefPO), their replacement in the mid-term by transition fuels (LNG and LPG), and a subsequent phase out of these fuels and their replacement by MeOH, NH3 and H2. With respect to the emissions' threshold (ETS regulation) we assumed again a moderate emissions reduction target of 25% by 2030, 55% by 2040 and 75% by 2050. The demand for shipping services by 2050 was based on a moderate Shared Socioeconomic Pathway scenario, the SSP2. Its moderate growth assumption projects an increase of shipping demand by 50% until 2050, with steady economic growth and moderate population increases, with shipping demand rising steadily due to global trade expansion. Climate policies progress at a moderate pace, with shipping regulations becoming stricter, in line with the emissions reduction target we set. Greece's maritime sector is expected to follow this trend, focusing on adopting greener fuels while meeting growing global demand for shipping services. Another important factor that the MaritimeGCH model can incorporate is the consideration of various technologies that aim to improve efficiencies and reduce emissions, for example the mid-term measures of GHG strategy of IMO (IMO, 2023) In this case study application, we indicatively consider four such interventions as a combination for emissions-reduction. These refer to: (1) Engine power optimization (tuning engines for efficiency, potentially using advanced fuel injection systems, and optimizing speed for reduced fuel consumption and emissions) (Wang and Meng, 2012); (2) Port call technology for optimal timing and approach of ships entering a port (reducing thus emissions associated with waiting times and speed) (Nikghadam et al., 2024); (3) Propulsion systems for more efficient and less emission-intensive mechanisms (Inal et al., 2022; Nguyen et al., 2021); and finally (4) ship hull cleaning technologies to reduce its traction and resistance in water, which can subsequently reduce the associated emissions (Kim et al., 2024; Stark et al., 2022). These technologies can be represented implicitly in the model as they have a certain cost (which can be added in the cost function), and can lead to a certain percentage of CO_2 emissions reductions.

Figure 1. Results of the application to the Greek fleet, including: the fleet composition (stock and new ships); investment and operational costs; fuel demand and the associated costs; the CO2 emissions compared to the ETS threshold, and the associated penalty.

The results (Figure 1) show the fleet evolution, investment, and operational metrics until 2050. As assumed, there is a steady growth in the shipping demand services according to the SSP2 projection, which demands a respective increase in the number of vessels for its coverage (exceeding 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 new ships’ results reveal periodic investments in fleet expansion, replacing aging vessels with a sharp rise around 2050, mainly due to a combination of increased demands and retiring ships. 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 growing fleet rises consistently the operational costs (reaching approximately €5,000 million by 2050), reflecting also the adoption of the various technologies. 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. This shift correlates with the gradual increase in fuel costs, implying investments in more expensive but cleaner alternatives. Here, it is important to note that we assume the fuels costs remain the same within our planning period. So, the fuel costs rise from around €50 million in the early years to over €100 million by 2050.

Moreover, we see that the CO_2 emission are gradually reducing. This is an important finding, proving that although the shipping demand and the fleet size increase, the transition to cleaner fuels and the adoption of emission reduction technologies can outweigh that. According to the ETS regulation assumption, we also observe an increasingly stringent cap, though instances of excess emissions are evident in the early periods. These excess emissions drive the “ETS Penalty” costs, which spike notably during periods of non-compliance, peaking at over €1,800 million early before declining as emissions approach compliance with the threshold. This trend underscores the effectiveness of regulatory measures, encouraging a transition towards sustainable practices that lower both emissions and associated penalties over time. Overall, the results suggest a maritime strategy balancing fleet growth, compliance, and cost-effectiveness.

4. Relevance to the SDGs

This model serves as a powerful Investment Decision Support Tool (IDST), offering insights into the long-term economic, operational, and environmental impacts of different fleet and fuel choices. It can answer questions on the cost implications of fleet expansion, the financial impact of transitioning to cleaner fuels, and the return on investments in emission reduction technologies. Additionally, it evaluates compliance with environmental regulations like the ETS, while meeting objectives such as the CII, and projects potential penalty costs for non-compliance. By modeling future operational costs, CO_2 emissions, and fuel demands, it helps investors make informed decisions that align with sustainability goals and market demands.

It is also important to note that such an IDST makes the problem and solutions of maritime operations quite relevant to various SDGs. In particular, it supports SDG 7: Affordable and Clean Energy, and specifically Target 7.2, by modeling transitions to cleaner energy sources, such as LNG, MeOH, NH_3, and H_2, in the shipping industry. This promotes a shift towards renewable and low-carbon fuels, enhancing the share of sustainable energy in maritime operations. Additionally, there is a direct relation to SDG 9: Industry, Innovation, and Infrastructure, where the Target 9.4 is met as the model evaluates scenarios that involve investments in new ship technologies and retrofitting current fleets (which is explicitly modeled in the scenario configuration under the emission-reduction technologies considered). These investments enhance fuel efficiency, reduce emissions, and optimize operational practices, reflecting sustainable industrial upgrades. A related point, is that the MaritimeGCH model also directly supports SDG 13: Climate Action. By focusing on CO_2 emissions reduction, a key component of its outputs, it captures the SDG Target 13.2, referring to the decarbonization efforts. This is crucial as the model simulates the impacts of stricter CO_2 emission thresholds, but it is quite realistic in allowing their exceedance. It also evaluates potential penalties for non-compliance, and demonstrates the effectiveness of adopting emission reduction measures aligned with international and European climate regulations. By emphasizing climate-responsive strategies, it ensures that maritime operations are increasingly integrated into broader environmental policies. Furthermore, the model relates to SDG 14: Life Below Water, and the Target 14.1. While primarily addressing CO_2 emissions, the shift to cleaner fuels also reduces the risk of ocean acidification and marine pollution, supporting marine conservation. Finally, SDG 8: Decent Work and Economic Growth, and more relevant to Target 8.4, is represented through the model's scenarios that demonstrate how sustainable practices in shipping can meet increasing demands while promoting economic growth. By detailing efficient resource use and sustainable fleet expansion, the MaritimeGCH model highlights how the maritime industry can achieve economic resilience while prioritizing environmental stewardship.

Therefore, this step of the analysis has to emphasize the importance of testing alternative model runs against different scenarios. That way, one can get a full view of the strengths and weaknesses a model may manifest under different conditions of input data. This could reveal, at a number of levels, the linkage between economic considerations and global developmental goals in order to align investment decisions with the SDGs. The strength of this methodological rigor not only gives more relevance to the model but also lays a foundation for evidence-based policymaking, cognizant of sustainable and equitable growth trajectories.

5. Concluding Remarks

In this chapter, the MaritimeGCH model, an integrated maritime fleet optimization model, was presented. Its mathematical description was outlined, and its potential for scenario exploration considering various policy-relevant cases was demonstrated for the Greek shipping sector.

Greece's maritime sector can contribute to UN-identified Sustainable Development Goals (SDGs) such as Goal 14 on Life Below Water, Goal 13 on Climate Action, and Goal 8 on Decent Work and Economic Growth. As one of the largest shipping countries, Greece's significant fleet plays a crucial role in international trade and economic stability. However, the industry's heavy reliance on fossil fuels and contribution to GHG emissions pose challenges in aligning with international decarbonization targets and broader SDG objectives. Greece is committed to mitigating its environmental impact by adopting cleaner technologies and energy-efficient vessel designs.

At the same time, one could say that Greece has made quite evident progress with the advancement of SDGs. The Sustainable Development Report 2024 shows that the country, with a score of 78.71, was ranked 29th in the world. The Hellenic Statistical Authority-ELSTAT regularly reports information on SDG indicators, thus allowing transparency and data insight into the developmental trajectory of Greece.

Greece has implemented measures to address environmental challenges in shipping, presenting a comprehensive package in November 2024 to reduce the carbon footprint of coastal shipping and ports, backed by public investments of up to €860 million.

Greece has also joined international collaborations to advance sustainable maritime. In October 2024, the country became a participant in the Clean Energy Marine Hubs initiative, advancing decarbonization through clean energy infrastructure development (Safety4Sea, 2024). Furthermore, the establishment of the Maritime Emissions

Reduction Centre in Athens, supported by leading Greek shipping companies and Lloyd's Register, reflects a concerted effort to enhance energy efficiency and reduce emissions across the industry (Lloyd's Register, 2024).

The Maritime GCH model offers a framework for integrating scientific insights into policy and decision-making, emphasizing economic efficiency and environmental considerations. This evidence-based approach addresses complex shipping industry issues, a model that can be replicated by other maritime nations. Greece's maritime sector, using scientific research and technological innovation, demonstrates how well-thought-out policies can help achieve the Sustainable Development Goals (SDGs). This holistic, systems-based approach promotes sustainable development in the industry, making Greece an interesting case study for sustainable development.

Code Availability: The model's script along with indicative datasets are publicly available at GitHub: https://github.com/Alamanos11/MaritimeGCH

References

Alamanos, A. (2024). The Global Climate Hub. *Nature Sustainability*, 1–2. https://doi.org/10.1038/s41893-024-01289-8

Alamanos, A., & Garcia, J. A. (2024). Optimization Examples for Water Allocation, Energy, Carbon Emissions, and Costs. *Encyclopedia*, *4*(1), Article 1. https://doi.org/10.3390/encyclopedia4010022

Alamanos, A., Nisiforou, O., Garcia, J.A., Papadaki, L. & Koundouri, P. (2024). Integrated fleet optimization under techno-economic shipping and environmental constraints: the MaritimeGCH model. DOI: 10.13140/RG.2.2.35892.87680. Available at: https://github.com/Alamanos11/MaritimeGCH

Al-Enazi, A., Bicer, Y., Okonkwo, E. C., & Al-Ansari, T. (2022). Evaluating the utilisation of clean fuels in maritime applications: A techno-economic supply chain optimization. *Fuel*, *322*, 124195. https://doi.org/10.1016/j.fuel.2022.124195

Clarksons Research. (2023). Clarksons Research. https://www.clarksons.com/research/

European Commission. (2021). "Proposal for a Directive amending Directive 2003/87/EC as regards aviation's contribution to the Union's economy-wide emission reduction target and appropriately implementing a global market-based measure".

European Commission. (2022). *Decarbonising maritime transport – FuelEU Maritime—European Commission*. https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

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

European Commission. (2003) EU emissions trading system (EU ETS). https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (2023). *FAQ: Maritime transport and the EU Emissions Trading System (ETS)*. Climate Action. https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector/faq-maritime-transport-eu-emissions-trading-system-ets_en

Faber, J., et al. (2020). Fourth IMO Greenhouse Gas Study 2020. International Maritime Organization (IMO).

Franz, S., & Bramstoft, R. (2024). Impact of endogenous learning curves on maritime transition pathways. *Environmental Research Letters*, *19*(5), 054014. https://doi.org/10.1088/1748-9326/ad3bce

Franz, S., Campion, N., Shapiro-Bengtsen, S., Bramstoft, R., Keles, D., & Münster, M. (2022). Requirements for a maritime transition in line with the Paris Agreement. *iScience*, *25*(12). https://doi.org/10.1016/j.isci.2022.105630

Han, Y., Ma, W., & Ma, D. (2023). Green maritime: An improved quantum genetic algorithm-based ship speed optimization method considering various emission reduction regulations and strategies. *Journal of Cleaner Production*, *385*, 135814. https://doi.org/10.1016/j.jclepro.2022.135814

Handl, G. (2023). Decarbonising the shipping industry: A status report. *The International Journal of Marine and Coastal Law*, 1(aop), 1–62.

Hellenic Statistical Authority (ELSTAT). (2024). Monitoring Progress Towards the SDGs in Greece. Retrieved from https://www.statistics.gr/en/sdgs

IMO (International Maritime Organization). (2021). "Guidelines on the operational carbon intensity indicator and the calculation methods (CII Guidelines, G1)". MEPC.336(76).

IMO. (2016). "Guidelines for the development of a ship energy efficiency management plan (SEEMP)". MEPC.282(70).

IMO. (2022). *Rules on ship carbon intensity and rating system enter into force*. https://www.imo.org/en/MediaCentre/PressBriefings/pages/CII-and-EEXI-entry-into-force.aspx

Inal, O. B., Charpentier, J.-F., & Deniz, C. (2022). Hybrid power and propulsion systems for ships: Current status and future challenges. *Renewable and Sustainable Energy Reviews*, *156*, 111965. https://doi.org/10.1016/j.rser.2021.111965

International Maritime Organization. (2019). *Data Collection System (DCS) for fuel oil consumption of ships*. Regulation 22A of MARPOL Annex VI. https://www.imo.org

International Maritime Organization. (2023). EEXI and CII: Infographic 01 – General information [PDF]. https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/EEXI%20and%20CII%20Sheets/Infographic%2001_general.pdf

Johnson, H., et al. (2013). "Improving the energy efficiency of ships: What matters?". Marine Policy, 39, 154-159.

Johnson, H., Johansson, M., & Andersson, K. (2013). Barriers to improving energy efficiency in short sea shipping: An action research case study. Journal of Cleaner Production, 52, 329-336

Kim, D.-H., Alayande, A. B., Lee, J.-M., Jang, J.-H., Jo, S.-M., Jae, M.-R., Yang, E., & Chae, K.-J. (2024). Emerging marine environmental pollution and ecosystem disturbance in ship hull cleaning for biofouling removal. *Science of The Total Environment*, *906*, 167459. https://doi.org/10.1016/j.scitotenv.2023.167459

Koilo, V. (2024). Decarbonization in the maritime industry: Factors to create an efficient transition strategy. Environmental Economics, 15(2), 10–21. https://doi.org/10.21511/ee.15(2).2024

Koundouri, P., Alamanos, A. & Sachs, J. (2024). Innovating for Sustainability: The Global Climate Hub. Working Paper, Athens University of Economics and Business, 2024. https://files.unsdsn.org/2024.the.GCH.pdf

Koundouri, P., Alamanos, A., Plataniotis, A., Stavridis, C., Perifanos, K., & Devves, S. (2024). Assessing the sustainability of the European Green Deal and its interlinkages with the SDGs. *Npj Climate Action*, *3*(1), 1–10. https://doi.org/10.1038/s44168-024-00104-6

Kühne and Nagel. (2024). Greece Commits to Greening its Coastal Shipping Network. Retrieved from https://mykn.kuehne-nagel.com

Lloyd's Register. (2024). Maritime Emissions Reduction Centre Established in Athens. Retrieved from https://www.lr.org

MarineTraffic. (2024). Live ship tracking and AIS data.https://www.marinetraffic.com/en/ais/home/

Meng, Q., Wang, S., Andersson, H., & Thun, K. (2014). Containership routing and scheduling in liner shipping: Overview and future research directions. Transportation Science, 48(2), 265-280.

Nguyen, H. P., Hoang, A. T., Nizetic, S., Nguyen, X. P., Le, A. T., Luong, C. N., Chu, V. D., & Pham, V. V. (2021). The electric propulsion system as a green solution for management strategy of CO emission in ocean shipping: A comprehensive review. *International Transactions on Electrical Energy Systems*, *31*(11), e12580. https://doi.org/10.1002/2050-7038.12580

Nikghadam, S., Vanga, R., Rezaei, J., & Tavasszy, L. (2024). Joint scheduling of vessels and vessel service providers for enhancing the efficiency of the port call process. *Maritime Economics & Logistics*. https://doi.org/10.1057/s41278-024-

00290-4
Nisiforou, O., Shakou, L. M., Magou, A., & Charalambides, A. G. (2022). A Roadmap towards the Decarbonization of Shipping: A Participatory Approach in Cyprus. *Sustainability*, *14*(4), Article 4. https://doi.org/10.3390/su14042185
Perčić, M., Vladimir, N., & Fan, A. (2021). Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. *Renewable and Sustainable Energy Reviews*, *148*, 111363. https://doi.org/10.1016/j.rser.2021.111363
Psaraftis, H. N. (2019). "Decarbonization of maritime transport: to be or not to be?". Maritime Economics & Logistics, 21(3), 353-371.
Psaraftis, H.N. and Kontovas, C.A. (2013) Speed Model for Energy-Efficient Maritime Transportation: A Taxonomy Survey. Transportation Research Part C, 26, 331-351. https://doi.org/10.1016/j.trc.2012.09.012
Regulation (EU) 2003/87 of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. (2003). *Official Journal of the European Union*, L 275, 32–46. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32003L0087
Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. (2015). *Official Journal of the European Union*, L 123, 55–76. https://eur-lex.europa.eu/eli/reg/2015/757/oj/eng
Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. (2023). *Official Journal of the European Union*, L 234, 48–100. https://eur-lex.europa.eu/eli/reg/2023/1805/oj/eng
Safety4Sea. (2024). Greece Joins Clean Energy Marine Hubs Initiative. Retrieved from https://safety4sea.com
SDSN. Sustainable Development Solutions Network. https://www.unsdsn.org/ (2022).
SDSN. UNSDSN CLIMATE GLOBAL HUB - Systemic pathways to Climate Neutrality and Climate Resilience https://unsdsn.globalclimatehub.org/
Stark, C., Xu, Y., Zhang, M., Yuan, Z., Tao, L., & Shi, W. (2022). Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell-Powered Ships. *Journal of Marine Science and Engineering*, *10*(3), Article 3. https://doi.org/10.3390/jmse10030388
Sustainable Development Report. (2024). Sustainable Development Report 2024: Rankings and Scores. https://dashboards.sdgindex.org
United Nations Conference on Trade and Development. (2024). Seaborne trade. fhttps://unctadstat.unctad.org/datacentre/dataviewer/US.SeaborneTrade
United Nations Conference on Trade and Development. (2023/2024 Maritime profile: Greece. https://unctadstat.unctad.org/CountryProfile/MaritimeProfile/en-GB/300/index.html
Wang, S., & Meng, Q. (2012). Sailing speed optimization for container ships in a liner shipping network. Transportation Research Part E: Logistics and Transportation Review, 48(3), 701-714.