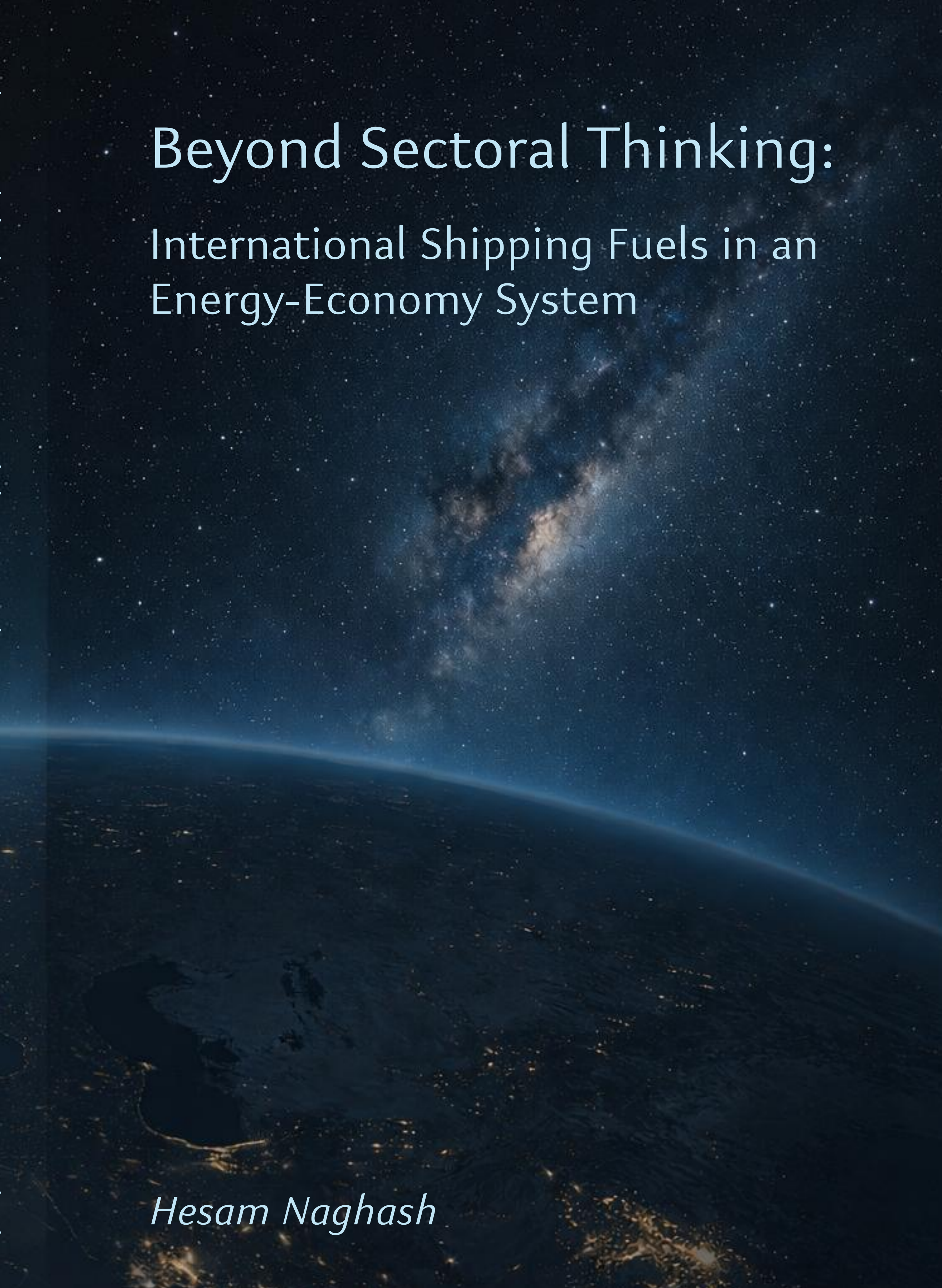
Citation (APA)
Naghash, H. (2026). *Beyond Sectoral Thinking: International Shipping Fuels in an Energy-Economy System: Techno-economic assessment of seaborne trade, fleet, fuel, and emission pathways within an integrated assessment model.* [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:cbf4be86-357e-42a3-ab85-c2b36281d3e3



Beyond Sectoral Thinking:

International Shipping Fuels in an Energy-Economy System

Hesam Naghash

Propositions

accompanying the dissertation

Beyond Sectoral Thinking: International Shipping Fuels in an Energy-Economy System

by

Hesam NAGHASH

1. Actionable insights into maritime decarbonization require an integrated perspective; sectoral precision alone misleads decision-making. (This thesis)
2. Alternative fuels are unavoidable for deep decarbonization of global shipping, and ammonia is central enough that the debate should move from “if” to “how”. (This thesis)
3. As national climate commitments weaken, internationally governed sectors like shipping can reignite collective climate action and transmit momentum to other sectors. (This thesis)
4. Paradoxically, bringing a work laptop on holiday in an attempt to relieve stress only makes it worse.
5. When an activity is economically profitable and technically feasible, its moral acceptance by society tends to follow.
6. Unity collapses when danger fades; history has repeatedly shown that another crisis will restore it.
7. The climate change problem was created by single-dimensional thinking; seeking a single solution repeats that error.
8. Gaming demonstrates that humanity is capable of extraordinary dedication, provided the goal involves imaginary dragons.
9. Most PhD dissertations change science marginally, but writing one changes the scientist profoundly.
10. Over time, artificial intelligence mirrors its user through repeated interaction, much like a child mirrors a parent.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotor Dr. ir. J.F.J. Pruijn, and promotor Prof. dr.ir. D.L. Schott.

Beyond Sectoral Thinking: International Shipping Fuels in an Energy-Economy System

Techno-economic assessment of seaborne trade, fleet, fuel, and emission pathways within an integrated assessment model

Hesam NAGHASH

Beyond Sectoral Thinking: International Shipping Fuels in an Energy-Economy System

Techno-economic assessment of seaborne trade, fleet, fuel, and emission pathways within an integrated assessment model

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, Prof.dr.ir. H. Bijl,
chair of the Board for Doctorates
to be defended publicly on
Monday, 4th May 2026 at 12:30

by

Hesam NAGHASH

This dissertation has been approved by the promotors.

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The research presented in this dissertation was conducted as part of the EU-funded Horizon 2020 project MAGPIE (sMArt Green Ports as Integrated Efficient Multimodal Hubs, grant agreement No. 101036594).

Keywords: Climate change, International trade, Alternative fuels, Energy economics, Integrated assessment modeling, Maritime shipping

Cover: designed by Hesam Naghash and generated by ChatGPT 5.2.

ISBN: 978-94-6537-508-3

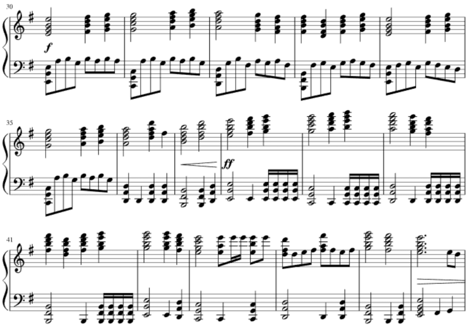
An electronic copy of this dissertation is available at
`https://repository.tudelft.nl/`.

Printed in the Netherlands

آب کم جو تشنگی آور به دست تا بجوشد آب از بالا و پست

Seek not water—seek thirst instead,
So that water may surge forth, from above and below

-Rumi

To love...in all its forms

-Neal Acree

CONTENTS

SUMMARY

International maritime shipping is essential to global trade yet remains one of the most challenging sectors to decarbonize. Its dependence on fossil fuels, long asset lifetimes and competition with other industries for clean energy carriers create deep structural barriers. At the same time, the sector's emissions sit at the intersection of global and sectoral regulation, which means that climate policy can affect shipping both directly and indirectly. Because of these features, understanding how shipping transitions under different policy and technology conditions requires a framework that links trade, energy systems and the global economy in a consistent way.

The thesis begins by reviewing the existing literature, which shows that current projections for maritime shipping vary widely. This diversity of outcomes is traced not to uncertainty alone but to differences in model structure, treatment of demand, technology assumptions and policy design. Sectoral models represent ships and fuels with detail but do not capture how trade and the wider energy system respond to climate policy. Integrated Assessment Models capture these broader dynamics but have so far represented shipping too crudely to assess fuel transitions or policy impacts with confidence. The review identifies the criteria required for a suitable approach: it must link shipping demand to global trade and economic development, treat fuel supply and vessel turnover consistently with the energy system, include a wide set of technological options and support structured scenario comparison. These insights provide the basis for the framework developed in the thesis.

Building on these requirements, the thesis develops an integrated modeling system in which trade flows, shipping activity, fleet evolution, fuel production, energy use and policy instruments interact within a single coherent structure. Global bilateral trade is represented with a cargo-specific econometric model that responds to income growth, oil prices and carbon pricing. This allows shipping demand to emerge endogenously rather than from external assumptions. Trade activity is then translated into fuel use and fleet capacity using a distance- and weight-based allocation method that maps flows to vessel types and sizes in a way that remains consistent as global trade patterns change. These relationships, calibrated to IMO data, form a physical and economic link between the global economy and the maritime transport system.

Fuel competition, technology choice and policy effects are evaluated within the WITCH Integrated Assessment Model, using the same structure that governs other hard-to-abate sectors. This unified system makes it possible to analyse how shipping competes with industry, power and transport for zero-carbon fuels, how global carbon pricing reshapes fuel availability, how sector-specific regulation affects fleet turnover and how these interactions determine emissions over time. The framework captures both the upstream expansion of electrolytic hydrogen and ammonia production under ambitious climate policy and the downstream consequences for maritime fuel choice.

The results show that carbon pricing lowers the long-run cost of zero-carbon fuels by driving investment in clean hydrogen and ammonia, but this does not ensure their adoption in shipping because other sectors can absorb the available supply. Sector-specific regulation accelerates fuel switching within shipping, but its effectiveness depends on parallel expansion of clean fuel production. The availability of ammonia is decisive: when permitted, it becomes the main zero-carbon fuel for long-distance transport under stringent mitigation and enables a full phase-out of oil by mid-century. When ammonia is excluded, shipping must rely on methanol, biofuels and limited hydrogen, none of which scale sufficiently, leading to higher cumulative emissions and in some cases unsatisfied energy demand.

The thesis also examines how these global outcomes unfold across regions. Using the same model structure, regional trade profiles, resource availability, and policy environments produce distinct transition pathways. East and Southeast Asia decarbonize earliest under strong global carbon pricing, but are most exposed to ammonia constraints. The Americas and Europe progress more steadily, supported by greater biomass availability that maintains momentum even when ammonia is limited. The Middle East and Africa transition later, but can become important suppliers and consumers of alternative fuels due to their renewable resource potential. These differences arise not from different climate ambitions but from regional structures that shape the feasibility and cost of different fuel pathways.

Taken together, the thesis provides a modeling framework in which trade, fleet dynamics, fuel supply, and policy choices are treated as an interconnected system. It shows that maritime decarbonization depends simultaneously on global climate signals, sector-specific regulation, and the availability of scalable fuels. Deep emissions reductions remain feasible, but only when policies and fuel production expand in tandem and when regional differences are recognised rather than assumed away. The framework developed here enables a more realistic assessment of shipping's transition and clarifies the conditions under which global and regional pathways remain achievable.

SAMENVATTING

Internationale maritieme scheepvaart is essentieel voor de wereldhandel, maar behoort tegelijkertijd tot de sectoren die het moeilijkst te decarboniseren zijn. De sterke afhankelijkheid van fossiele brandstoffen, de lange levensduur van schepen en de concurrentie met andere sectoren om schone energiedragers vormen diepe structurele barrières. Tegelijkertijd bevinden de emissies van de scheepvaart zich op het snijvlak van mondiale en sectorspecifieke regelgeving, waardoor klimaatbeleid de sector zowel direct als indirect kan beïnvloeden. Door deze kenmerken vereist inzicht in hoe de scheepvaart zich ontwikkelt onder verschillende beleids- en technologieomstandigheden een analysekader dat handel, energiesystemen en de wereldeconomie op een consistente manier met elkaar verbindt.

Het proefschrift begint met een overzicht van de bestaande literatuur, waaruit blijkt dat huidige projecties voor de maritieme scheepvaart sterk uiteenlopen. Deze diversiteit in uitkomsten is niet uitsluitend het gevolg van onzekerheid, maar vooral van verschillen in modelstructuur, de behandeling van vraag, technologische aannames en beleidsontwerp. Sectorspecifieke modellen beschrijven schepen en brandstoffen gedetailleerd, maar leggen niet vast hoe handel en het bredere energiesysteem reageren op klimaatbeleid. Geïntegreerde Assessment Modellen (IAM's) vangen deze bredere dynamiek wel, maar hebben de scheepvaart tot nu toe te grof weergegeven om brandstoftransities of beleidsimpact met voldoende vertrouwen te kunnen analyseren. De literatuurstudie identificeert daarom de criteria voor een geschikte benadering: deze moet de vraag naar scheepvaart koppelen aan mondiale handel en economische ontwikkeling, brandstofvoorziening en vlootvernieuwing consistent behandelen binnen het energiesysteem, een breed spectrum aan technologieën omvatten en gestructureerde scenariocomparaties mogelijk maken. Deze inzichten vormen de basis voor het in dit proefschrift ontwikkelde raamwerk.

Op basis van deze vereisten ontwikkelt het proefschrift een geïntegreerd modelsysteem waarin handelsstromen, scheepvaartactiviteit, vlootontwikkeling, brandstofproductie, energiegebruik en beleidsinstrumenten binnen één samenhangende structuur op elkaar inwerken. Mondiale bilaterale handel wordt gemodelleerd met een cargospecifiek econometrisch model dat reageert op inkomensgroei, olieprijzen en koolstofbeprijzing. Hierdoor ontstaat de vraag naar scheepvaart endogeen, in plaats van te worden opgelegd via externe aannames. Handelsactiviteit wordt vervolgens vertaald naar brandstofgebruik en vlootcapaciteit via een afstands- en gewicht-gebaseerde allocatiemethode die handelsstromen toewijst aan scheepstypen en -groottes, op een manier die consistent blijft wanneer mondiale handelsstructuren veranderen. Deze relaties, gekalibreerd op basis van IMO-gegevens, vormen een fysieke en economische koppeling tussen de wereldeconomie en het maritieme transportsysteem.

Concurrentie tussen brandstoffen, technologische keuzes en beleidsmaatregelen worden geanalyseerd binnen het WITCH Integrated Assessment Model, met dezelfde structuur als voor andere moeilijk te decarboniseren sectoren. Dit geïntegreerde systeem maakt het mogelijk om te onderzoeken hoe de scheepvaart concurreert met industrie, elektriciteitsproductie en transport om nul-koolstofbrandstoffen, hoe mondiale koolstofbeprijzing de beschikbaarheid van brandstoffen beïnvloedt, hoe sectorspecifieke regelgeving de vlootvernieuwing versnelt en hoe deze interacties gezamenlijk het emissieverloop bepalen. Het raamwerk legt zowel de opschaling van elektrolytische waterstof- en ammoniakproductie onder ambitieus klimaatbeleid vast als de daaruit voortvloeiende gevolgen voor de brandstofkeuze in de scheepvaart.

De resultaten laten zien dat koolstofbeprijzing de langetermijnkosten van nul-koolstofbrandstoffen verlaagt door investeringen in schone waterstof en ammoniak te stimuleren, maar dat dit op zichzelf geen garantie biedt voor grootschalige toepassing in de scheepvaart, omdat andere sectoren het beschikbare aanbod kunnen absorberen. Sectorspecifieke regelgeving versnelt de brandstofomschakeling binnen de scheepvaart, maar de effectiviteit daarvan hangt af van een gelijktijdige uitbreiding van de productie van schone brandstoffen. De beschikbaarheid van ammoniak blijkt doorslaggevend: wanneer het is toegestaan, wordt het onder stringente mitigatiescenario's de dominante nul-koolstofbrandstof voor langeafstandstransport en maakt het een volledige uitfasering van olie tegen het midden van de eeuw mogelijk. Wanneer ammoniak wordt uitgesloten, moet de scheepvaart vertrouwen op methanol, biobrandstoffen en beperkte hoeveelheden waterstof, die geen van alle voldoende schaal bereiken. Dit leidt tot hogere cumulatieve emissies en in sommige gevallen tot onvervulde energievraag.

Het proefschrift onderzoekt tevens hoe deze mondiale uitkomsten zich regionaal manifesteren. Binnen dezelfde modelstructuur leiden regionale handelsprofielen, hulpbronnenbeschikbaarheid en beleidscontexten tot uiteenlopende transitiepaden. Oost- en Zuidoost-Azië decarboniseren het vroegst onder sterke mondiale koolstofbeprijzing, maar zijn het meest kwetsbaar voor beperkingen in ammoniakbeschikbaarheid. De Amerika's en Europa volgen een geleidelijker pad, ondersteund door een grotere beschikbaarheid van biomassa die de transitie gaande houdt wanneer ammoniak beperkt is. Het Midden-Oosten en Afrika maken de transitie later, maar kunnen belangrijke producenten en gebruikers van alternatieve brandstoffen worden dankzij hun potentieel aan hernieuwbare energie. Deze verschillen vloeien niet voort uit uiteenlopende klimaatambities, maar uit regionale structuren die de haalbaarheid en kosten van verschillende brandstofroutes bepalen.

Gezamenlijk biedt dit proefschrift een modelleringskader waarin handel, vlootdynamiek, brandstofvoorziening en beleidskeuzes als een onderling verbonden systeem worden behandeld. Het laat zien dat de decarbonisatie van de scheepvaart gelijktijdig afhankelijk is van mondiale klimaatsignalen, sectorspecifieke regelgeving en de beschikbaarheid van schaalbare brandstoffen. Diepe emissiereducties blijven haalbaar, maar alleen wanneer beleid en brandstofproductie zich in samenhang ontwikkelen en wanneer regionale verschillen expliciet worden erkend in plaats van genegeerd. Het hier ontwikkelde raamwerk maakt een realistischer beoordeling van de transitie van de scheepvaart mogelijk en verduidelijkt onder welke voorwaarden mondiale en regionale transitiepaden uitvoerbaar blijven.

1

INTRODUCTION

1.1. CLIMATE & SHIPPING CONTEXT

"Every action matters. Every bit of warming matters. Every year matters. Every choice matters." — IPCC (2018)

Climate change is the defining challenge of the 21st century. It is already reshaping ecosystems, economies, and societies, with evidence ranging from accelerating sea-level rise to more frequent extreme weather events and biodiversity loss. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasized that avoiding the worst impacts requires rapid and far-reaching transformations across all sectors of the global economy [1]. The Paris Agreement, signed in 2015, represents a collective recognition of this urgency, setting the target of limiting global average temperature increase to well below 2 °C, with efforts to limit it further to 1.5 °C by the end of the century [2]. Achieving this objective requires a rapid reduction in greenhouse gas emissions to net zero by the second half of the century.

The transport sector accounts for roughly 15–18% of global CO_2 emissions. International maritime shipping alone accounts for about 2.5–3% of global emissions, corresponding to approximately 1.0 $GtCO_2$ per year [3–5]. Shipping forms the backbone of the global economy, transporting more than 80% of world trade by volume and over 70% by value, or more than 10 billion tonnes of energy commodities, bulk resources, and manufactured goods annually [6–8]. Despite accounting for a modest share of global emissions, this scale of activity makes shipping a deeply systemic sector. The sector operations connect global supply chains and rely almost entirely on fossil fuels for propulsion. Therefore, it is both an enabler of globalization and a driver of climate change. Yet, unlike many other sectors, international shipping was not included in the Paris Agreement. Instead, its regulation falls under the International Maritime Organization (IMO), a specialized United Nations agency [2].

In 2018, IMO established a pilot strategy to reduce shipping-related GHG emissions. This strategy aimed to achieve a pathway for GHG emissions consistent with the Paris Agreement temperature goals, translated into the objective of limiting total emissions from international shipping in 2050 to 50% of the 2008 level [9]. IMO's ultimate goal was to completely decarbonize the marine transportation sector [8, 10]. In 2023, the IMO revised its strategy, aiming for net-zero life-cycle GHG emissions around 2050 rather than 2100. This updated goal underscores the sector's commitment to global climate mitigation efforts [11]. The updated 2023 Strategy also set more ambitious goals for net-zero emissions by 2050 and boosting the use of zero and low-emission fuels by 2030 [12]. Most recently, during April 2025, the 83rd session of the IMO's Marine Environment Protection Committee (MEPC83) convened in London to address key environmental challenges in shipping. Delegates agreed to levy a portion of ships' well-to-wake greenhouse gas emissions, obliging vessels that exceed their carbon intensity targets to purchase remedial units at tiered prices [13, 14]; however, in October 2025, the implementation was postponed by at least one year.

International shipping is widely regarded as a *hard-to-abate* sector, primarily because direct electrification of long-haul vessels is infeasible due to the limited range and energy density of batteries. As a result, deep decarbonisation depends on the large-scale deployment of more complex and demanding alternative energy carriers, such as ammonia, hydrogen, and other synthetic fuels, whose supply chains and infrastructure remain at an early stage of development. Shipping also exhibits long asset lifetimes, with only about 3–4% of the global fleet replaced each year, which slows the turnover of existing fossil-fuel-based vessels [7]. Against this structural backdrop, the IMO's ambitious decarbonisation goals are far from guaranteed to be achieved, and establishing clear, feasible pathways consistent with recent regulations remains a central challenge for the sector [15].

1.2. CHALLENGES AND GAPS

Despite being a hard-to-abate sector, the shipping sector has made progress through various energy-efficiency measures. Operational practices such as slow steaming, optimized vessel speeds, wind assistance, and improved hull designs enhance fuel efficiency and reduce emissions, but their overall contribution to decarbonization remains limited to 5-25% reduction [16]. Historically, the IMO has already introduced regulatory measures including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), the Ship Energy Efficiency Management Plan (SEEMP), and the Carbon Intensity Indicator (CII), to improve vessel efficiency [17–20].

However, their effectiveness is still in question. Although improved energy efficiency can help lower emissions, it will not be enough to decarbonize the sector entirely. Low- and zero-carbon fuels will therefore be critical [21]. The 4th IMO GHG study suggested that new energy carriers are required, as other measures will not achieve the required reduction in GHG emissions [3]. Similarly, many studies have concluded that without the inclusion and adoption of alternative fuels, full decarbonization of the shipping sector is unlikely [22]. The International Energy Agency (IEA) also warns that these efforts alone fall short of what is needed to keep climate targets within reach [5].

Currently, green fuel production is very limited, and no clear best option is available, resulting in a large set of fuels and converters competing for this role [23]. Reaching net-zero emissions will require a large-scale shift to alternative energy carriers, including green ammonia, hydrogen, methanol, biofuels, and LNG. Yet, it remains unclear how to develop, produce, and scale them economically. Each option faces challenges related to production costs, scalability, infrastructure requirements, and lifecycle emissions, while competition with other sectors such as aviation, heavy industry, and power generation further complicates the transition[1]. In short, while the goal of achieving a zero-emission, sustainable shipping sector is clear, the specific pathways to achieve it have not yet been defined. Alternative fuels are needed, but their economic viability under different circumstances remains uncertain.

Given these uncertainties, including technology readiness, fuel availability, economic viability, and policy design, the scope for emission abatement in shipping and its interaction with the broader energy system remain fundamentally uncertain. To address this complexity, models are required to systematically analyze interactions, test alternative assumptions, and evaluate the implications of different decarbonization pathways for the shipping sector. So far, sectoral models have been used extensively to explore the decarbonization of international shipping [24]. While these studies provide detailed analyses of technologies, fuels, and policy measures, they often treat shipping as an isolated sector, overlooking its strong connection to energy, economy, and other sectors. In practice, bilateral trade dynamics between countries and regions determine the scale and structure of shipping activity demand. This demand, combined with assumptions about technological progress and operational efficiency, defines fuel consumption and total energy requirements. The composition of the energy mix required to meet this demand then determines emissions, all of which are shaped by regional and global policy environments. Because these elements are deeply interdependent, shipping cannot be assessed in isolation. In that regard, it is essential to consider interactions with other transport sectors, as they share common fuel supply chains. Developments in aviation, road transport, and industry can significantly influence fuel availability, cost, and technological progress in maritime shipping [25]. Moreover, technological improvements and the transition to alternative marine fuels are closely linked to similar advancements in other energy-using sectors [26].

By contrast, integrated and general equilibrium modeling approaches provide a global perspective on the interactions between energy, the economy, and the climate system. These frameworks have been widely applied to analyze the implications of long-term climate mitigation strategies and have played an important role in shaping climate governance and policy. They represent the world's energy, land-use, agricultural, and environmental systems in an interconnected manner, enabling examination of relationships across sectors and regions over time. Within such approaches, contrasting yet plausible scenarios are often developed to explore complexity and uncertainty systematically. These scenarios reveal how different factors interact, either reinforcing or counteracting one another, thereby supporting the comparison of potential outcomes and the design of informed climate policies [24, 27–29]. However, international shipping remains underrepresented in many integrated models, signaling a need to refine and expand these models. Long-term scenarios often pay relatively little attention to emissions from international transport, typically projecting shipping demand or emissions using aggregated relationships with income, without sectoral specificity [29]. As a result, shipping is frequently treated as an exogenous or peripheral component of the energy–economy system, rather than as an endogenous sector whose demand, fuel choices, and emissions co-evolve with broader economic and energy transitions.

Problem Statement : This exposes a fundamental disconnect between detailed sectoral representation and coherent system-wide modeling. Sectoral approaches provide technological detail but lack integration with the broader economy, while integrated approaches provide system-wide coverage but lack sectoral realism. This duality leaves policymakers without the tools to assess how international shipping might evolve under climate constraints, or how policies targeted at the sector interact with economy-wide mitigation strategies. A further conceptual gap concerns the representation of future scenarios. Forecasting precise shipping trajectories is impossible due to uncertainties in trade patterns, technology costs, and political choices. What is possible, however, is to construct pathways, internally consistent scenarios that reflect alternative assumptions and policies. Pathways are not predictions but structured explorations of possible futures. They illuminate trade-offs, interdependencies, and answer "*What if..?* questions. This thesis adopts this pathways perspective, situating shipping not as a deterministic forecast but as an uncertain system whose trajectories depend on choices made under deep uncertainty. By developing maritime shipping models and coupling them to an integrated framework, this work enhances the representation of shipping within economy-wide models, enabling a more comprehensive assessment of how trade dynamics, technological transitions, and policy measures interact to shape the sector's decarbonization pathways.

As illustrated in Figure 1.1, the evolution of global climate governance, integrated modeling, shipping regulatory action, and sectoral shipping studies has mainly unfolded in parallel over the past five decades. While integrated models and global policies have progressively expanded to represent economy-wide mitigation pathways, maritime regulations and modeling frameworks have evolved within their own institutional and analytical boundaries. The limited interaction between these domains created an *integration gap*; in which sectoral realism and system-wide coherence remained disconnected.

1.3. RESEARCH AIM & QUESTIONS

This thesis aims to conduct an integrated techno-economic assessment of international shipping within global climate mitigation pathways. By embedding detailed representations of trade, fleets, and fuels within an integrated framework, the thesis examines how global policies, technological change, and economic drivers interact to shape the decarbonization of maritime transport. The objective is to quantify possible futures while clarifying the conditions, trade-offs, and interactions that determine the feasibility of different pathways.

The main research question, therefore, is: "*How can an integrated modeling framework be developed and applied to evaluate climate policy options for international maritime shipping, and assess how sector-specific and economy-wide policies shape decarbonization pathways through their interactions with trade, fuels, and the broader energy system under deep uncertainty?*

To address this question, the thesis is structured around a sequence of sub-research questions. Five central sub-research questions follow this:

1. How have existing models and studies projected the future of international maritime shipping, what assumptions and methodological choices drive their outcomes, and which criteria can be derived to identify the most suitable modeling approach for assessing decarbonization pathways?

2. How can bilateral trade and shipping demand be represented within an integrated framework to capture how climate policies and carbon pricing reshape regional, global, and cargo-specific trade patterns?

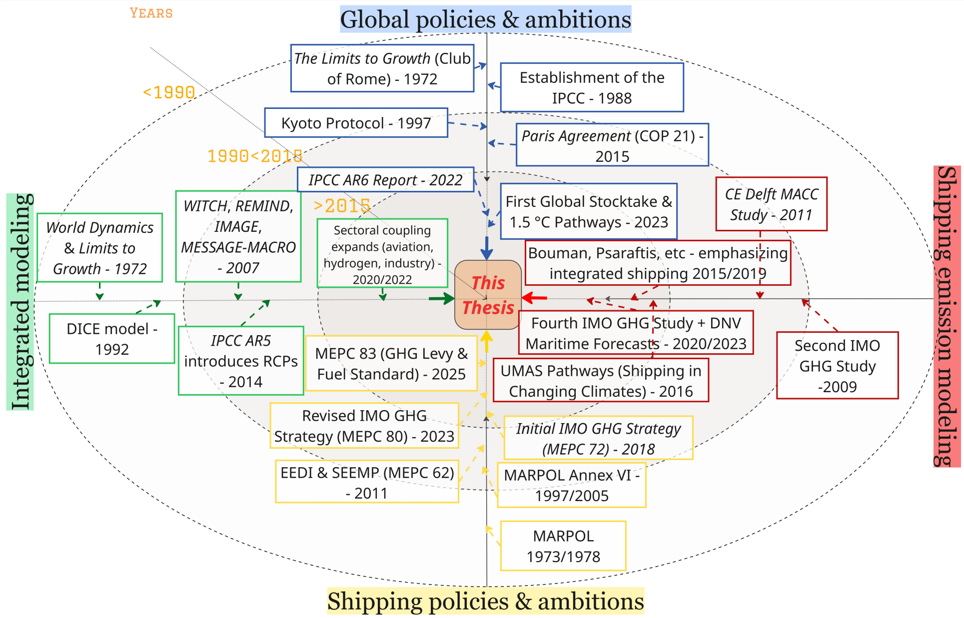


Figure 1.1.: **Historical evolution of global and sectoral frameworks for shipping decarbonization.** The figure traces four parallel domains: global climate policy (blue), integrated modelling (green), IMO policy development (yellow), and sectoral shipping research (red). These domains evolved largely independently since the 1970s, creating an *integration gap* between detailed sectoral analyses and system-wide policy assessment. Global agreements such as the *Paris Agreement* (2015) and *IPCC AR6* (2022) strengthened economy-wide targets, while the IMO introduced its own instruments. Sectoral studies (e.g., CE Delft 2011; UMAS 2016; Psaraftis 2019; DNV 2023) provided technological depth but remained weakly linked to integrated models. Only recently have these strands begun to converge, with emerging work, including this thesis, embedding maritime transport into frameworks that connect trade, fuels, and policy.

3. How can projected shipping activity in ton-miles be converted into estimates of energy demand, fuel use, and required fleet capacity across vessel types and sizes?

4. How do global carbon pricing, sectoral regulations, and alternative fuel availability interact within an integrated techno-economic perspective to define international shipping's fuel mix, costs, and emission pathways, and their spillovers across the wider energy system?

5. How do regional differences in trade structures, resource availability, and policy conditions translate into distinct decarbonization pathways for international shipping?

1.4. METHODOLOGICAL APPROACH

The thesis addresses these questions using a structured, stepwise approach. Chapter 2 presents a systematic review of existing shipping projections and modeling studies, analyzing how future scenarios are constructed, what assumptions underpin them, and which criteria define suitable modeling frameworks. This review identifies key limitations in current approaches and motivates integrating shipping into broader climate–energy models. With the methodological foundations established, Chapter 3 operationalizes these insights by developing an econometric gravity-based model of bilateral maritime trade, differentiated by cargo type. The model estimates trade elasticities and is linked with the integrated framework to endogenize shipping demand, thereby improving the representation of trade responses to macroeconomic drivers and climate policies in global scenarios. Chapter 4 translates trade flows into energy requirements by mapping cargoes onto vessel classes and sizes, enabling realistic estimation of fuel consumption and fleet investments, and grounding the analysis in physical and economic terms. Chapter 5 extends an Integrated Assessment Model (IAM), specifically the WITCH model, with a dedicated shipping module that includes multiple marine fuel pathways, cost curves with learning effects, vessel categories, and policy instruments such as global carbon budget and IMO-specific measures. This extension enables analysis of interactions among technology, policy, and trade, and captures how shipping decarbonization feeds back into technology deployment and mitigation outcomes across the broader energy system, providing one of the first integrated assessments of shipping decarbonization pathways. Finally, Chapter 6 explores regional decarbonization trajectories, examining how variations in trade structures, resource availability, and policy environments shape heterogeneous transitions across world regions and influence fuel adoption, fleet composition, and emission outcomes.

Through these steps, as indicated in Figure 1.2, the thesis bridges sectoral detail and global integration. It constructs a coherent framework that links trade, fleet, fuel, and policy within a single global model, enabling systematic exploration of pathways to net-zero shipping.

1.5. CONTRIBUTIONS AND NOVELTY

This thesis makes several contributions relevant to both the scientific and policy communities and to ongoing stakeholder initiatives. It contributes directly to the long-term shipping and supply chain work package of the *MAGPIE* project[1] , an EU-funded initiative aimed at developing smart, green, and integrated port solutions for the

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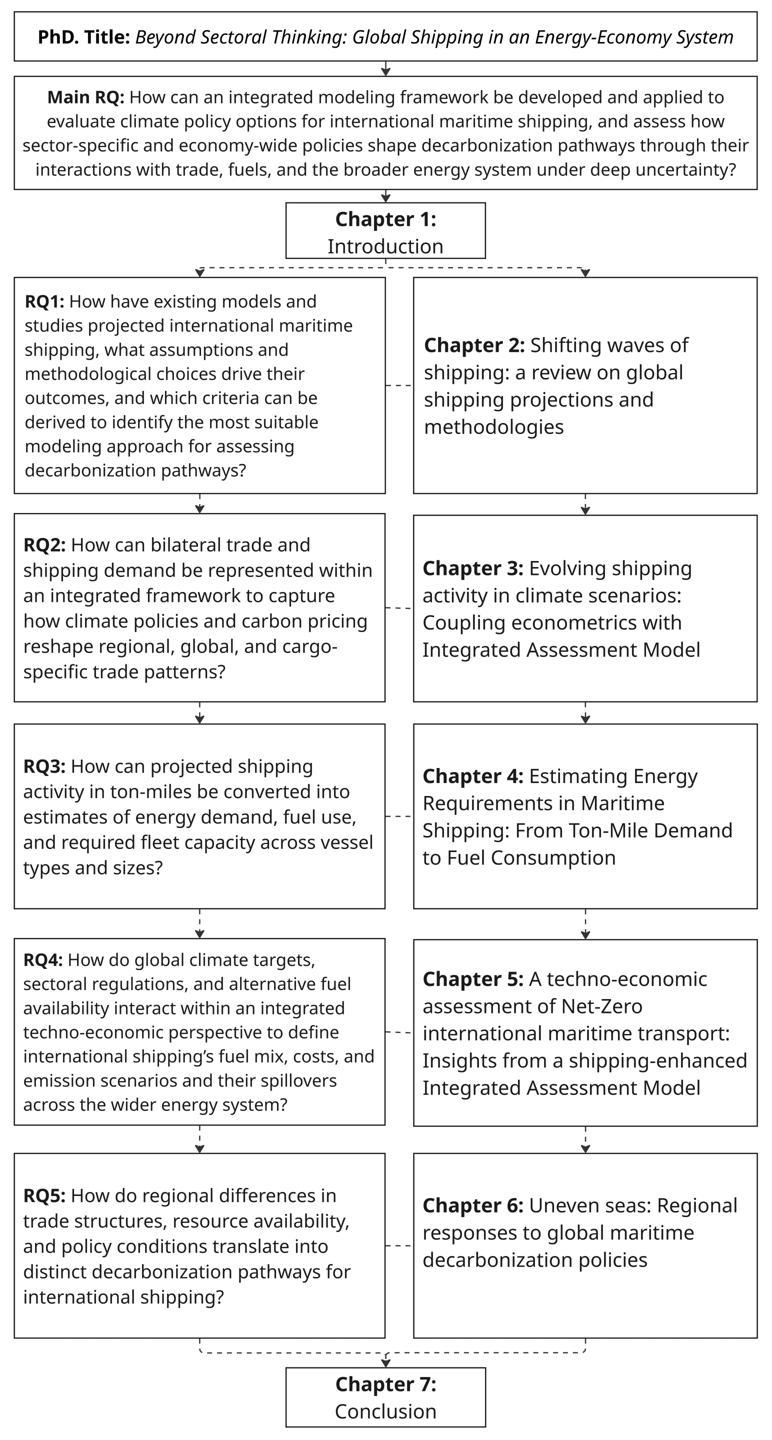
[1] https://www.magpie-ports.eu/

energy transition. The modeling frameworks and insights developed in this thesis support policymakers by providing quantitative tools for informed decision-making on maritime decarbonization strategies. At the same time, they offer scientists and researchers a foundation for conducting more detailed analyses of trade dynamics, fuel transitions, and integrated climate–energy interactions in future studies.

- Systematic review of projections: It provides a structured assessment of existing shipping projections, identifying why many fail to align with the IMO's updated net-zero ambition.
- Endogenized shipping demand: It develops a novel econometric module that integrates cargo-specific and regional maritime trade into an IAM, addressing a long-standing omission in global climate models.
- Energy–fleet linkage: It establishes a robust connection between ton-mile demand, energy consumption, fleet structure, and shipbuilding investments, enabling a realistic assessment of future capacity needs.
- Shipping-enhanced IAM: It extends a widely used IAM with a maritime module, providing one of the first sets of global scenarios that capture the interplay of alternative fuels, policy measures, and economy-wide dynamics for international shipping, including impacts on mitigation burdens in other transport and energy sectors.

Together, these contributions advance the representation of shipping in integrated assessment modeling and provide policy-relevant insights into the sector's transition to net-zero. They demonstrate that no single measure or fuel will be sufficient, but that decarbonization will depend on the alignment of global trade patterns, fuel developments, and coordinated international policies.



PhD. Title: *Beyond Sectoral Thinking: Global Shipping in an Energy-Economy System*

Main RQ: How can an integrated modeling framework be developed and applied to evaluate climate policy options for international maritime shipping, and assess how sector-specific and economy-wide policies shape decarbonization pathways through their interactions with trade, fuels, and the broader energy system under deep uncertainty?

Chapter 1: Introduction

RQ1: How have existing models and studies projected international maritime shipping, what assumptions and methodological choices drive their outcomes, and which criteria can be derived to identify the most suitable modeling approach for assessing decarbonization pathways?

Chapter 2: Shifting waves of shipping: a review on global shipping projections and methodologies

RQ2: How can bilateral trade and shipping demand be represented within an integrated framework to capture how climate policies and carbon pricing reshape regional, global, and cargo-specific trade patterns?

Chapter 3: Evolving shipping activity in climate scenarios: Coupling econometrics with Integrated Assessment Model

RQ3: How can projected shipping activity in ton-miles be converted into estimates of energy demand, fuel use, and required fleet capacity across vessel types and sizes?

Chapter 4: Estimating Energy Requirements in Maritime Shipping: From Ton-Mile Demand to Fuel Consumption

RQ4: How do global climate targets, sectoral regulations, and alternative fuel availability interact within an integrated techno-economic perspective to define international shipping's fuel mix, costs, and emission scenarios and their spillovers across the wider energy system?

Chapter 5: A techno-economic assessment of Net-Zero international maritime transport: Insights from a shipping-enhanced Integrated Assessment Model

RQ5: How do regional differences in trade structures, resource availability, and policy conditions translate into distinct decarbonization pathways for international shipping?

Chapter 6: Uneven seas: Regional responses to global maritime decarbonization policies

Chapter 7: Conclusion

Figure 1.2.: Thesis outline

2

LITERATURE REVIEW

This chapter examines how existing models and studies have projected the future of international maritime shipping and identifies the assumptions and methodological choices that drive their results. By comparing sectoral and integrated approaches, it shows that the wide divergence in published pathways reflects structural differences in model design rather than uncertainty alone. This diagnosis motivates the central premise of the thesis: that shipping decarbonization cannot be assessed in isolation, but must be embedded consistently within a global energy–economy framework.
This chapter is presented *as published* as the peer-reviewed article *"Shifting Waves of Shipping: A Review of Global Shipping Projections and Methodologies"* in the *Journal of Shipping and Trade* (2024), DOI: 10.1186/s41072-024-00187-8. It establishes the conceptual and methodological criteria that guide the modeling choices developed in the subsequent chapters.

2.1. INTRODUCTION

Climate change is one of the major and complex challenges that humans must address in the current era. The international body for assessing the science related to climate change—the Intergovernmental Panel on Climate Change (IPCC)—reports that an increase in temperature may cause irreversible damage, including rising sea levels, extreme weather events, loss of biodiversity, and ocean acidification. Greenhouse gases, with CO_2 being the most abundant, are responsible for this temperature rise [1]. The transportation sector accounted for approximately 15% of net global anthropogenic greenhouse gas (GHG) emissions in 2019 [2]. The international shipping sector is an important contributor to emissions, accounting for approximately 1.06 GtCO_2/year. A substantial portion of this (0.74

GtCO_2/year) is related to international freight transport [3, 4]. This sector accounts for 80–90% of global trade, moving over 10 billion tonnes of containers, solid and liquid bulk cargo annually across the world's oceans [5]. Given the historically upward trend in shipping activity and the undeniable linkages among trade, shipping, and economic growth, these emissions are expected to increase. In 2019, world trade increased by 18% relative to 2016, further exacerbating emissions in the maritime shipping sector [6]. Also, the shipping sector, which was not initially included in the Paris Agreement, has been slower to adopt decarbonization measures than other sectors. As a result, the share of greenhouse gas emissions from shipping is expected to grow.

In 2018, the United Nations body responsible for environmental regulation of international shipping—the International Maritime Organization (IMO)—established a pilot strategy to reduce shipping-related GHG emissions. This strategy aims to achieve a pathway of GHG emissions consistent with the Paris Agreement temperature goals. This has been translated into the objective of limiting total emissions from international shipping in 2050 to 50% of the emission amount in 2008 [7]. IMO's ultimate goal was to completely decarbonize the marine transportation sector [5, 8]. Recently, IMO has adopted the updated 2023 Strategy to lower GHG emissions from ships, setting more ambitious goals for net-zero emissions by 2050 and boosting the use of zero and low-emission fuels by 2030 [9].

Operational measures, such as slow steaming and optimizing vessel speeds, can lead to enhanced fuel efficiency and reduced emissions. Slower speeds improve wind assistance and contribute to overall fuel savings. However, these impacts are limited [10]. The 4th IMO GHG study suggested that new energy carriers are required, as other measures will not be able to achieve the required reduction of GHG emissions [4]. Also, [11] concludes that without including and adopting alternative fuels, it is unlikely that the shipping sector will be fully decarbonized.

Currently, green fuel production is very limited, and no clear best option is available, leading to a large set of fuels and converters applying for this role [3]. In short, while the target of achieving a zero-emission, sustainable shipping sector is clear, the specific pathways to reach this goal have not yet been defined. Also, we know that alternative fuels are needed, but we need to know the economic viability of these fuels under different circumstances. In that regard, it is essential to consider the interplay with other transport sectors, as they share a common fuel supply chain. This means that developments in sectors like aviation, road transport, and industry can significantly influence fuel availability, cost, and technological development in maritime shipping.

Over time, many models have been developed with various scopes and objectives. However, a robust model with specific features is needed to identify pathways toward a zero-carbon international maritime shipping sector by mid-century. Models that integrate the sector with the broader economy, including supply and demand dynamics and technological options like alternative fuels, are required. These models should operate globally while also reflecting regional specifics and be capable of simulating diverse scenarios to evaluate the impacts of policies. Thus, five criteria for the models are defined, based on which the quality of existing studies will be assessed.

This paper aims to find the most suitable way to develop models to find pathways toward decarbonization targets. This is done in two main parts. First, we look into existing ranges and scenarios to identify the current estimations and the assumptions impacting these estimations. Secondly, based on the defined criteria for the objective and context of this paper, the most suitable modeling method will be evaluated. Combining the insights obtained from valid assumptions and modeling methods, in line with a new philosophy of looking at the problem, leads to appropriate modeling direction.

Therefore, the main question to answer is: "*What are the projected trajectories & modeling methods for international shipping activity, fuel mix, and* CO_2 *emissions under future economic and regulatory scenarios?*" To address this question, it’s crucial to recognize the central role of legislation as the primary driver for the shipping industry’s transition to sustainability.

Section 2 discusses the five defined criteria, followed by the methodology for collecting and selecting the literature. Section 3 presents reviews of the selected literature, divided into three subsections: shipping activity demand, fuel supply, and emissions. Section 4 analyzes the underlying assumptions and the suitability of modeling frameworks. Conclusions and recommendations for future studies are presented in Section 5.

2.2. METHODOLOGY

In the methodology section, we reviewed previous studies on the future outlook of international shipping. These studies were selected based on their relevance to the research question and goals. The search was conducted in the Scopus and Google Scholar databases using specific keywords, such as "International maritime shipping", "pathway", "future", "projection", "emission", "supply", and "demand." The selection of these keywords was intentional. "International maritime shipping" was included as it is the primary focus of the research. Keywords such as "emission," "supply," and "demand" were selected for their direct relevance to the research’s main components. The terms "pathway" and "projection" were selected for their implications regarding the trajectory and potential scenarios that shipping may follow in the long term, offering insights into systematic changes. The term "future" was incorporated to ensure that the research covered forward-looking studies that extend beyond historical data, including trends, predictions, and strategic planning relevant to maritime shipping. Articles not in English were excluded from the search. Articles that did not align with the research, as indicated by their titles, summaries, and keywords, were removed. Online tools were used to identify additional relevant publications related to the existing literature, ensuring comprehensive coverage.

In this literature review, the Multi-Criteria Decision Analysis (MCDA) technique is employed to systematically rate and rank the selected papers. MCDA is a method for analyzing decision options and identifying the most preferred values based on a set of criteria that determine their relevance to the problem [12]. Given the global nature of climate change and shipping and the complex interactions of the economy, five criteria for the models used in the literature are defined and justified in the following.

1. **Sectoral integration scope:** Sectoral modeling primarily focuses on a specific sector, in this case, maritime shipping, to understand factors related exclusively to that sector in isolation. However, integrated approaches adopt a more holistic view, accounting for a myriad of factors, including economic, social, and environmental variables. This type of model considers multiple factors, such as energy use, population growth, and economic development, to create future scenarios. Integrated approaches combine energy technology models with economic and climate models to assess various pathways. Such a comprehensive evaluation allows for an assessment of the feasibility of achieving distinct climate change mitigation goals [13]. A crucial dimension that supports the case for an integrated approach is the phenomenon of intersectoral knowledge spillover. This refers to the transfer of knowledge and ideas across different sectors of the economy [14]. Recognizing this effect augments the analysis by capturing technological knowledge influences that are not confined to a single sector [15]. To illustrate, consider the potential of hydrogen utilization and production for light-duty vehicles & energy storage. As this production escalates, the ensuing economies of scale could drive down the marginal costs over the years. Consequently, the now cheaper hydrogen could become a feasible option for marine transportation. Such interconnected impacts remain elusive to single-sector approaches. So, while looking at the shipping industry can be useful for short-term questions, an integrated approach is better for understanding the bigger picture, especially when considering implications like climate change mitigation.

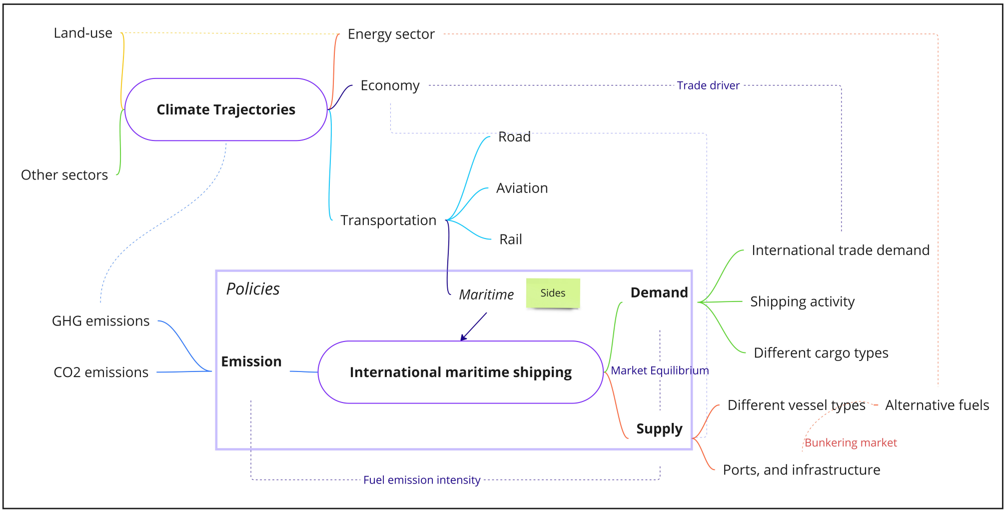


Figure 2.1.: The integrated nature of international shipping with other parts of the economy.

2. **Dimensionality:** Analyzing international maritime shipping through the lenses of demand, supply, and emissions offers a comprehensive perspective on the sector. Demand pinpoints the required shipping activity in tonne-nautical miles (ton.nm) or equivalent units, which subsequently informs the fuel demand side on how these needs can be met and by which fuels. The chosen supplying fuels, along with efficiencies, determine the emissions produced by the sector. Taking such an integrated approach provides a more accurate projection of future scenarios and improves the coherency among these different sides by ensuring consistent and aligned assumptions underlying the model. This integrated perspective mirrors the complexities of the shipping sector, making policy recommendations more grounded. In the past, some studies, like [16] and [17], have studied only one side, such as the supply side and emission side, respectively. In contrast, others, like [18], have embraced a wider perspective, addressing demand, emissions, and policy implications. The more sides of maritime shipping we incorporate, our understanding becomes clearer and more comprehensive. [Figure 2.1] illustrates the integrated nature of international maritime shipping within the broader picture and its impact on climate change. Transportation contributes to emissions, with maritime shipping being a significant sub-sector. Maritime shipping is driven by international trade demand, which is influenced by economic growth and macroeconomic factors. These economic drivers affect shipping activity (demand side), which in turn influences the

fuel supply and vessel types (supply side). These factors are regulated by specific policies, which determine the resulting emissions. These emissions contribute to greenhouse gas emissions, linking maritime shipping directly to climate trajectories. This chain underscores that international maritime shipping is a piece of a bigger puzzle.

3. **Technology Range:** The choice of either narrowing down on one or two technologies/fuels/vessels or exploring a wider range of options largely depends on the research question and study objectives. A focused study on a single technology, fuel, or ship type can provide detailed insights into its advantages and drawbacks. However, expanding the study to include various options gives a wider perspective. This includes understanding trade-offs, synergies, and the interplay between different technologies, fuels, vessels, and associated policy implications. A holistic view of various technologies, fuels, and vessels in climate target research becomes essential. Also, Including technologies like BECCS (Bioenergy with Carbon Capture and Storage) and DAC (Direct Air Capture) in the study is crucial since they have undeniable effects on the strategy and cost-effectiveness of climate targets [19]. Illustrating this, studies like those by [20], [21], and [22] focused on specific fuels like LNG, hydrogen, and drop-in biofuels, respectively. Contrastingly, research undertakings by [16] and [23] cast a wider net, investigating multiple alternative fuels.

4. **Geographical Scope:** The choice between a global or a region-specific study also depends on the research question and objectives. For this study, a global approach suits well because of the global nature of shipping and climate mitigation targets. A global study offers a detailed analysis of possible strategies for cutting emissions in the shipping sector while also recognizing the trade-offs and synergies among different geographic regions and policy alternatives. One important factor to capture in the global approach is international spillovers. This is when something big that happens in one country's economy or technology sector affects another country. For example, if one country comes up with a new technology, another country might learn from it and boost its industry after a time lag [24]. This shows why a global perspective is valuable. Also, a global study allows the inclusion of trade distances between bilateral regions, which is key to determining shipping demand activity. Supporting this stance, specific regional studies, such as those by [25] on China and [26] on Brazil, might illuminate regional intricacies but don't necessarily provide a comprehensive global snapshot.

5. **Scenario Evaluation:** The scope and depth of policies and scenar-

ios in the studies under review varied, with some offering a singular perspective while others presented a broader picture by considering multiple policies, regulations, or scenarios. Benchmarking multiple scenarios enriches the analytical depth, enabling a comparative evaluation of intervention effects. This range of scenarios allows us to explore different intervention and their impacts. Regulation measures like emission price controls, which may manifest as taxes contingent on fuel's pollutant profile, emission quantity controls that set carbon budgets over time frames, and subsidies dispensed by authoritative bodies to enhance specific industry sectors [27–30]. Emissions Trading System (ETS) is a mechanism that operationalizes the "polluter-pays principle" and incentivizes stakeholders to curtail their emissions. The ETS operates on a cap-and-trade foundation, allocating emission allowances to regulated entities. Notably, on July 14, 2021, the maritime sector's GHG emissions were proposed to be encompassed within the EU ETS's purview [31, 32]. Recently, the European Commission announced that Europe will include maritime emissions in its Emissions Trading System starting in 2024, covering emissions from large ships and incentivizing energy efficiency and low-carbon fuels to achieve climate neutrality by 2050 [33]. Other strategies include the bunker levy, which has the potential to precipitate notable short-term emission reductions. Additionally, IMO has ratified measures such as the Energy Efficiency Design Index (EEDI), which mandates efficiency benchmarks for vessels post-2012, along with the Energy Efficiency Existing Ship Index (EEXI), the Ship Energy Efficiency Management Plan (SEEMP), and the Carbon Intensity Indicator (CII) [34, 35]. Integrating this discussion with the role of scenario benchmarking, it becomes evident that such an analytical tool is indispensable for future planning, especially given the inherent uncertainties [36]. Comparing scenarios and policies helps decision-makers understand the range of future outcomes, enabling them to make informed decisions.

Based on the outlined criteria depicted in Figure 2.2, publications were evaluated on a scale from 0 to 10, with 2 points allocated for each criterion. Each criterion was assigned an equal weight. Regarding "Dimensionality", three sides of international maritime shipping: demand, supply, and emissions, are considered. For each side addressed, a score of 0.66 is awarded. For example, a study that focuses solely on emissions receives a score of 0.66, whereas a study that examines all three aspects achieves the full 2 points. Concerning other criteria, scores are awarded as either 0 or 2. To be clearer, for the "sectoral integration", "technology range", "geographical scope", and "scenario evaluation", a score of 0 means that the study is sector-specific (not integrated), incorporates only one technology, is region-specific, and includes a single or no scenario for benchmarking. In contrast, a score of 2 signifies that the study integrates across sectors, includes multiple technologies, has a global focus, and evaluates multiple scenarios, respectively. Then, studies with fewer than 4 points have been eliminated. A more detailed scoring table with details of scores of each criterion is presented in the Appendix A. Our review focuses on studies that show what the future might look like for the international maritime sector. We specifically examined research that presents at least one detailed scenario. Initially, 179 papers were found, out of which 104 were deemed relevant through skimming and were selected for further review. Among these, 28 studies were rated sufficiently. Studies that obtained the score but did not depict a future scenario are mostly used for qualitative assessment.

This approach is practical for selecting qualified publications for further analysis. We will now discuss the future predictions from the papers to better understand the outcomes and presented information. Then, the underlying assumptions will be evaluated.

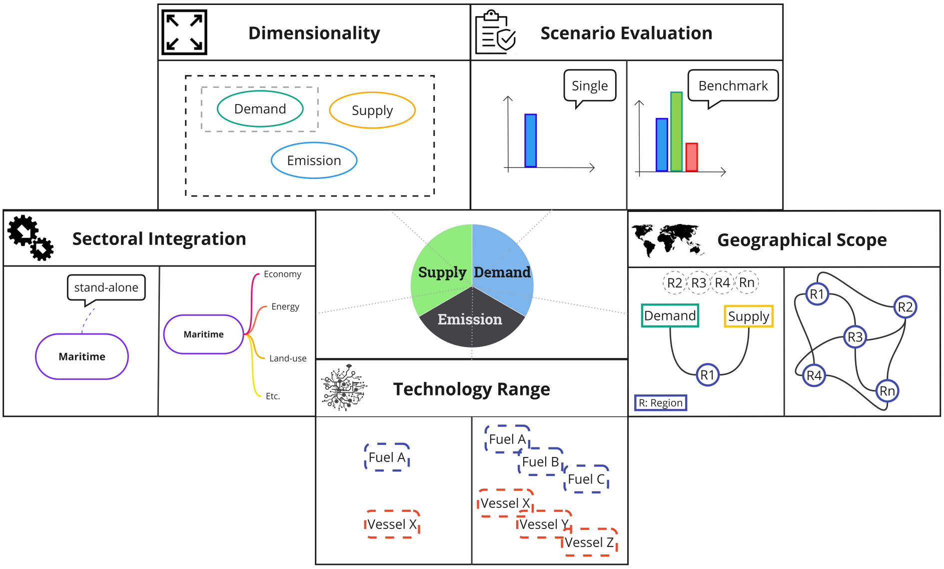


Figure 2.2.: Five defined criteria to match the study requirements for global carbon neutrality of the international shipping context.

2.3. MODELS AND FORECASTS

As mentioned earlier, the main sides of international maritime shipping are demand, supply, and emissions. The results for each one will be discussed hereafter. The data gathered and presented in this section is important to understand the current ranges and most repeated estimations in the field and also to understand what variables and assumptions derive those estimates. Note that different studies cover different sides, and thus, not all will be referred to in each section.

2.3.1. SHIPPING ACTIVITY DEMAND

In this research, demand refers to shipping activity or transport work in [mass × distance] units. In 2021, the total volume of international maritime trade, including crude oil, tanker trade, and dry cargo, was 10.98 GTon/year of loaded goods, as reported by the United Nations Conference on Trade and Development [37]. Ton-miles are estimated by Clarksons Research based on its data on seaborne trade and maritime distances as 58,988 billion ton-miles [38]. Various approaches have been employed to forecast demand. Traditionally, the relation between economic activity and freight transport is used to make forecasts of future aggregate freight flows and volumes [39]. Given the role of maritime transport in linking global supply chains and supporting trade, the relationship between GDP and trade is fundamental to all forecasting methods. Some studies estimate the future amount of shipping demand in mass-based metrics. Considering the objective of emission estimation, this gives an incomplete picture. To be able to link the demand to supplying fuels and, thereafter, to emissions, the discussion of shipping distances is imperative.

[18] employed the "IMAGE" integrated assessment model (IAM) to study various socio-economic pathways. A framework has been established by the climate change research community known as the Shared Socioeconomic Pathways (SSPs). This framework facilitates the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The pathways were developed over the last years as a joint community effort and describe plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change [40]. The projections are based on a demand-driven approach using the IMAGE model. The model generates yearly mass-based trade matrices for each product, which are used to obtain long-term projections of global trade according to six scenarios. They considered proxy ports for each region to calculate the shipping distance and estimate the transport work requirement. Their projections vary significantly across scenarios. The ’SSP2-mit’ scenario, based on global climate policy, forecasts a moderate increase in global maritime transport demand—31% by 2035 and 127% by 2100. In contrast, the ’SSP5’ scenario, which assumes fossil-fueled development and high economic growth, predicts much larger increases—145% by 2035 and 388% by 2100. Such variations indicate the profound influence of economic conditions, policy considerations, and population growth patterns on maritime transport demand.

[41] utilized their proprietary model, projecting a 50% increase in global maritime shipping demand by 2035 and 2050, with no data available for 2100. The tool is a demand-driven model in which the main drivers of energy demand are energy efficiency, population, and GDP. The absence of longer-term predictions underscores the challenges in forecasting farther into the future.

[42] leveraged the "TIAM" integrated assessment model for their projections. The methods used to forecast these scenarios are based on a combination of historical data analysis, expert input, and modeling. The authors used historical data on the production and trade of non-energy, non-containerized goods to estimate the relationship between changes in output and changes in trade. They then used this relationship to project future trade patterns based on scenario-specific adjustments. Their findings span a range of projected outcomes. From the 'MR2C' scenario, which anticipates a 26% increase of globally traded goods by 2035, to the 'GR' scenario, with a notable 63% rise by 2050, driven by high biomass and high CCS. On the other end of the spectrum, the 'HR' scenario, pivoting around a $4^{\circ}C$ rise and low biomass use, predicts a 106% increase of traded goods by 2035 and an even more significant 191% increase by 2050. The discussion of shipping distances is missing in the study, and the lack of transport work remains a shortcoming. The variance in these projections shows the significant role of environmental considerations and the impact of technology assumptions such as CCS and biomass availability.

[43] adopted the International Freight Model (IFM) for their analysis. the modeling approach used in the study is a four-step freight transportation modeling approach, which takes the OECD trade projection as an input. The International Freight Model (IFM) is designed to estimate the weight of commodities traded between countries, the choice between modes and transport routes used to transport these commodities based on transport network characteristics, and relevant socio-economic variables such as transport costs and time. The model consists of four components: trade flow disaggregation model, value-to-weight model, mode choice model, and route choice model. Their projections span from 'Scenario B', which anticipates a %40 global transport work demand increase by 2035, due to a 20% rise in intraregional trade combined with reduced fossil fuel commodity trade, to the 'Baseline' scenario projecting a %62 increase by 2035. These figures underscore the potential effects of regional trade dynamics.

[44] utilized a straightforward linear Regression analysis with GDP as the only independent variable. Their projections start with the 'TS1' scenario, which assumes an annual GDP growth of 2.3%. Under this scenario, traded goods are expected to increase by 22% by 2035 and by 78% by 2050. On the other end, the 'TS4' scenario predicts a more robust annual GDP growth of 3.6%. According to this scenario, traded

goods would see a 97% increase by 2035 and a 238% increase by 2050 in mass units. However, there is no discussion of shipping haul, and they only study the amount of traded goods on a mass basis. These figures demonstrate the direct correlation between GDP growth rates and the expansion of maritime transport demand.

A noteworthy contribution is by [45], who looked into the relationship of demand not just with GDP but also with the oil price. They employed a Vector Error Correction Model (VECM) to capture the long-run relationship of seaborne transport demand with world GDP and the price of oil, considering variations by countries' income. Although the study did not offer precise future demand values, its insights into the effects of oil price and income on maritime trade contribute to a better understanding of factors impacting future shipping demand.

[4, pp. 345–366] combined Regression analysis with IAM for their predictions. The study forecasts future transport work using two main methods. The logistic analysis assumes that the relationship between transport work and its driver (total GDP) follows a logistic (S-curve) pattern. On the other hand, the gravity model assumes a linear relationship based on panel data of bilateral trade flows. Both methods base their projections on historical trends and data from the Shared Socio-Economic Pathways (SSPs). In total, 24 scenarios are created. For a focused analysis, and to align with the scope of other studies, we selected 8 representative scenarios from the complete set. This selection was curated to include the scenarios with the lowest and highest projected growth rates, the 'middle of the road' SSP2-based projections, and to capture variations across different SSPs, RCPs, and modeling methods. Their projections span a diverse set of outcomes. The 'SSP4-RCP26-G' scenario projects the smallest increase of 16% by 2035, and the 'SSP5-RCP60-L' scenario predicts the most substantial rise of global transport work (ton.nm), potentially to more than doubling by 2050, reflecting a 210% increase. Under the SSP2 pathway, the 'SSP2-RCP19-G' scenario anticipates a 20% increase in transport work by 2035, whereas the 'SSP2-RCP26-L' foresees a significant increase to 91% by 2050. These results vary depending on the long-term socio-economic and energy scenarios, and different methods to establish the relation between transport work and relevant drivers. The logistic model results generally show higher growth than the gravity one.

Source	Tool	Units	Scenario	Description	Forecasted increase% (2020 baseline) 2035	2050	2100
[18]	IAM (IMAGE)	Ton-nm	SSP1	Sustainability - Rapid and sustainable economic growth, low inequality, and low population growth	63%	81%	81%
			SSP2	Middle of the Road - Moderate economic growth, medium inequality, and medium population growth	72%	109%	200%
			SSP2-mit	Climate policy scenario: This scenario assumes that a global climate policy is implemented	31%	54%	127%
			SSP3	Regional Rivalry - Uneven economic growth, high inequality, and declining population growth	45%	60%	154%
			SSP4	Inequality - High economic growth, high inequality, and declining population growth	54%	90%	100%
			SSP5	Fossil-fueled Development - High economic growth, high inequality, and high population growth	145%	228%	388%
[42]	IAM (TIAM)	Ton	GR	2C scenario - RCP2.6 - SSP1 (Sustainability) - high biomass - high CCS	36%	63%	-
			HR	4C scenario - RCP8.5 - SSP5 (Fossil-fueled Development) - low biomass - low CCS	106%	191%	-
			MR2C	2C scenario - RCP2.6 - SSP2 (Middle of the Road) - moderate biomass - moderate CCS	26%	40%	-
			MR4C	4C scenario - RCP8.5 - SSP2 (Middle of the Road) - moderate biomass - moderate CCS	45%	82%	-
[43]	International Freight Model (IFM)	Ton-km	Baseline	No additional measures are taken beyond those already in place	62%	-	-
			Scenario A	20% rise in intraregional trade	50%	-	-
			Scenario B	20% rise in intraregional trade + reduction in trade of fossil fuel commodities	40%	-	-
[44]	Regression analysis	Ton	TS1	Annual GDP growth of 2.3%	22%	78%	-
			TS2	Annual GDP growth of 2.8%	60%	150%	-
			TS3	Annual GDP growth of 3.1%	80%	180%	-
			TS4	Annual GDP growth of 3.6%	97%	238%	-
[41]	DNV model	Ton-nm	-	-	50%	50%	-
[4]	Regression analysis + IAM	Ton-nm	SSP2_RCP19_L	SSP2 (Middle of the Road) GDP projections, RCP 1.9, Logistics model	20%	34%	-
			SSP2_RCP26_G	SSP2 (Middle of the Road) GDP projections, RCP 2.6, Gravity model	46%	91%	-
			SSP4_RCP26_G	SSP4 (Inequality) GDP projections, RCP 2.6, Gravity model	16%	35%	-
			SSP4_RCP26_L	SSP4 (Inequality) GDP projections, RCP 2.6, Logistic model	44%	83%	-
			SSP5_RCP60_G	SSP5 (Fossil-fueled Development) GDP projections, RCP 6.0, Gravity model	56%	100%	-
			SSP5_RCP60_L	SSP5 (Fossil-fueled Development) GDP projections, RCP 6.0, Logistic model	91%	210%	-
			OECD_RCP26_L	OECD’s GDP projections, RCP 2.6, Logistics model	24%	43%	-
			OECD_RCP26_G	OECD’s GDP projections, RCP 2.6, Gravity model	37%	66%	-
[46]	International Freight Model (IFM)	Ton-km	Baseline	Trade agreements remain unchanged until 2060	60%	202%	-
			Bilateral	Bilateral "Free Trade Agreement" between major regions, cutting 50% of tariffs by 2030, abolishing tariffs by 2060,	62%	220%	-
			Multi-lateral	Global tariffs and agricultural support in regions are halved by 2060, Regulatory barriers adjusted in the FTA	70%	245%	-

Table 2.1.: Summary of seaborne trade demand’s evolution forecasts

Insights driven by the demand results are listed below:

- **Growth Variability:** Maritime transport demand growth is susceptible to diverse factors, with projections varying significantly across studies and scenarios.
- **Economic Imperatives:** Regional and global economic growth emerges as a pivotal determinant. Higher GDP growth rates generally correlate with steeper demand increases.
- **Environmental and Policy Interventions:** Scenarios rooted in sustainability or global climate policy tend to project moderated growth, emphasizing the dampening potential of environmental considerations and policy measures.
- **Modeling Complexity:** The choice of forecasting models and tools can influence outcomes, reflecting the inherent complexities in modeling maritime demand.
- **Future Uncertainties:** Long-term projections, especially those for 2100, are sparse, underscoring the inherent challenges in forecasting farther into an uncertain future.

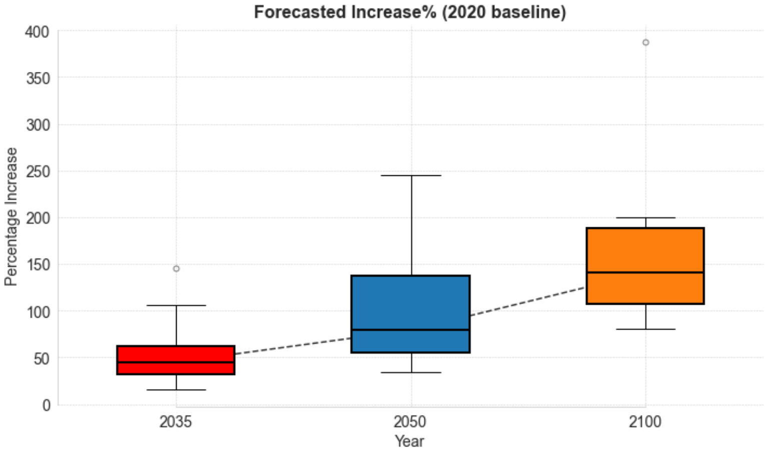


Figure 2.3.: Summary of global seaborne trade demand forecasts with uncertainties in 2035, 2050, and 2100.

The data of all studies are gathered in Table 2.1 and Figure 2.3. All in all they illustrate an obvious upward trend in the forecasted international shipping transport demand from 2035 to 2100. This trend, especially evident in the consistent growth rate between 2035 and 2050 and the increased variability in projections for 2050, underscores the expected progression of the sector. By 2100, the forecasts show less variation and seem more certain, but this is because there are fewer data points to consider. The wide range of forecasts for 2050 highlights the uncertainties or differing opinions on factors influencing transport demand during that period. Nonetheless, while the trajectory of maritime transport demand growth is upward, the magnitude and rate of this growth remain influenced by numerous socio-economic, policy, and environmental factors.

ENERGY EFFICIENCY

We need to consider the load factor and efficiency improvements to transition from transport demand in [mass × distance] units to the energy demand of ships in energy units. The load factor varies as some ships may travel fully loaded in one direction and return empty such as in the case of long-term contract oil carriers [47]. Also, not all vessels operate with full cargo, leading to more actual vessel usage and higher energy demand for a given transport demand. Efficiency improvements include technological advances, operational improvements, and the use of alternative energy sources. Technologically, optimizing the ship's hull design and applying specialized coatings can reduce water resistance and fuel consumption. Waste heat recovery systems utilize the engine's heat to enhance energy efficiency. Improving the ship's auxiliary systems, like lighting and air conditioning, reduces energy use, while exhaust treatment technologies lower emissions. Engine performance can be enhanced through design and material advancements, contributing to more efficient fuel use. Operationally, speed optimization, or slow steaming, reduces fuel consumption, while route optimization ensures travel efficiency and efficient cargo handling in ports and minimizes turnaround time. Regarding alternative energy sources, solar panels can provide auxiliary power, slightly reducing CO2 emissions, but their overall impact on the ship's power needs is limited. Wind-assistance technologies such as Flettner rotors and sails offer potential fuel savings, though adoption varies due to technological and industry factors [4, 10]. Wind propulsion, when paired with voyage optimization, can enhance carbon savings beyond 30% by leveraging wind conditions. Slower sailing speeds can further enhance these savings, with potential overall reductions of up to 60%, highlighting the considerable CO_2 reductions achievable with current technologies [48].

The approach in studies varies. Some studies modeled efficiency improvement, and it comes as a result of the model, while others make assumptions on exogenous improvement values. [18] defines two efficiency scenarios. The 'incremental gain scenario', utilizing efficient hull design and energy efficiency policies, assumes 30% and 35% improvement by 2050 and 2100 with the year 2020 as a reference point. The 'high gain scenario', by considering auxiliary propulsion improvement and slow steaming, assumes 40% and 50% improvement instead. In the first scenario, the total energy demand from international shipping lies in the range of 12-25 EJ in 2050 and 18-46 EJ in 2100. With higher efficiency gains, the energy demand lies in the range of 9-17 EJ in 2050 and 13-32 EJ in 2100. The efficiency scenarios are exogenously assumed. [26] modeled efficiency gains to align with EEDI, resulting in a more efficient fleet by 20% and 30% by 2030 and 2050 with respect to 2010. [49] defines 5 distinct energy efficiency packages. Baseline Energy Efficiency (EE) covers vessels built before 2015, focusing on essential operational and maintenance practices such as hull cleaning and engine tuning. Basic EE applies to ships made between 2015 and 2020, featuring hull design enhancements and propulsion system improvements. Enhanced EE, for the 2020–2025 period, plans to integrate advanced energy systems, including batteries and waste-heat recovery. Looking ahead to 2025–2030, Advanced EE aims to deploy renewable energy technologies such as hard sails and solar panels. Beyond 2030, Cutting-edge EE is set to introduce innovative technologies, including digital twins and onboard wind turbines, representing the leading edge of maritime energy efficiency development. Their model also assesses speed reductions at levels from 0% to 50%, analyzing fuel savings using data from over 2,000 vessels. Greater power savings occur at 10% and 20% reductions than at higher reductions due to wind and wave resistance. Fuel consumption decreases by 30-35% at 20% speed reduction and 60-67% at 50%. However, speed reduction reduces transport capacity, necessitating more vessels and increasing costs due to longer transit times. In [50], three efficiency packages are assumed. Package 1 integrates medium energy efficiency measures with a 10% speed reduction and transitions to zero-carbon fuels by 2035. Package 2 continues medium efficiency improvements and a 20% speed reduction from 2025. Package 3 maximizes energy efficiency technologies and operational measures with a 30% speed reduction, introducing decarbonization technologies and alternative fuels by 2035. This type of assumption could be valuable to understand the effects of different measures, but it does not necessarily reflect the real case scenarios. [4, pp. 400–404] shows an average efficiency improvement of around 15% for both gravity and logistic models applied within the maritime sector. Specifically, bulk carriers exhibit the highest potential for efficiency gains, while passenger ships show the least improvement. The improvements are the results of the models. In [51] model runs across various scenarios and forecasts significant efficiency improvements for maritime vessels by 2050, using 2010 as the baseline. Dry bulk carriers see enhancements ranging from 40% to 63%. Container ships are projected to achieve efficiency gains of 10% to 36%, while tankers are expected to achieve efficiency gains of 21% to 50%. [17] indicates that efficiency standards are often not captured adequately within IAMs, suggesting that the representation of efficiency should be improved.

2.3.2. SUPPLYING FUELS

In this research, supply refers to supplying fuels to the ships required to satisfy the demand for transport activity. The maritime sector currently depends almost entirely on oil-based, high-emitting fuels such as heavy fuel oil (HFO) and Marine Fuel Oil (MFO) [52]. The sector must diversify its energy sources to transition towards a more sustainable future, moving away from solely oil-based options. The International Maritime Organization's (IMO) decarbonization target emphasizes the need for this shift, and the exploration of alternative carbon-neutral fuels has gained momentum [16, 53, 54].

To make informed choices, understanding the advantages and disadvantages of each potential fuel is essential. [23] provides a detailed assessment of the strengths and limitations of alternative marine fuels. LNG stands out due to its relatively low cost and the availability of mature infrastructure and technologies. However, its storage requirements and limited ability to meet stringent CO_2 reduction targets remain key concerns. Often regarded as a transition fuel, LNG is frequently highlighted for its potential bridging role as the sector moves toward lower-carbon pathways [55]. The study in [56] applies a life-cycle assessment (LCA) to compare heavy fuel oil, marine gas oil, gas-to-liquid fuels, and LNG, including exhaust treatment options. It finds that LNG substantially reduces acidification and eutrophication impacts but delivers only modest reductions in global warming potential, on the order of 8–20%. Hydrogen offers a potential route to zero emissions, particularly when used in fuel cells and produced near ports, but its low energy density, high cost, and limited infrastructure pose major challenges. Ammonia, which can be used in both combustion engines and fuel cells, is constrained by toxicity concerns, high operating costs, and the emissions associated with current production pathways. Biofuels, including methanol and HVO, align well with carbon-neutral targets and existing vessel technologies, yet face challenges related to cost, limited supply, and fuel quality variability [57]. Electricity enables zero-emission operation with high efficiency, but its application is currently limited to short-range, low-power vessels due to high capital costs and battery technology constraints. As a result, uncertainty remains high regarding the future role of these fuels in the maritime energy mix, reflecting their limited presence today. The ultimate composition of future fuel pathways depends on a range of interacting technical, economic, and policy factors, as discussed in the studies that follow.

Table 2.2 lists the main advantages and disadvantages of alternative marine fuels, and Table 2.3 presents a comprehensive summary of maritime shipping's projected fuel mix for 2050, as indicated by studies.

Fuel	**Advantages**	**Dis-advantages**
LNG	• Competitive fuel price • Available infrastructure and technologies	• Must be stored in insulated tanks • Cannot comply with huge CO_2 reduction
Hydrogen	• Enable zero-emission (with fuel-cell) • Can be produced from electrolysis near ports	• Low energy density (50% of LNG) and large storage tanks • Extensive flammability range imposes the need for safety mitigating measures at an added cost • Expensive CAPEX and OPEX are around three times greater than LNG and viable production likely decades away • Absence of supply, bulk storage, and bunkering infrastructure
Ammonia	• Can be used in various combustion engines as well as fuel cells • Can be stored at relatively low pressure and high temperature (liquefied ammonia)	• High toxicity imposes the need for safety mitigating measures at an added cost • Excessive high OPEX – green ammonia is up to 4x LNG cost • Absence of bunkering and bulk infrastructure along major cargo routes • Current production generates undesirable high GHG emissions.
Biofuel (Methanol, HVO, etc.)	• Can be carbon neutral • Compatible with existing infrastructure and engine systems	• Expensive • Extremely limited due to land competition for food • Production capacity and bunkering availability • Quality and consistency of production varies; lack of agreed fuel standards, • High NOx and Particulate Matter emissions
Electricity	• Enable zero-emission • High efficiency	• Prohibitive CAPEX costs; battery technology not practicable for large oceangoing ships, battery costs could exceed the new build cost of a vessel • Applicability - limited to short-range low-power coastal vessels

Table 2.2.: General advantages and disadvantages of alternative marine fuels.

Source	Tool	Scenario	Description	Fuel mix of International maritime shipping in 2050					
				Oil-based	LNG	Biofuels	Ammonia/Hydrogen	Methanol	Electricity
[49]	DNV model	A	IMO 2018 ambitions, low biofuels	32-38%	20-29%	33-43%	0-1%	1-2%	3-4%
		B	IMO 2018 ambitions, low efuels	34-39%	19-26%	0-38%	3-14%	0%	3-4%
		C	IMO 2018 ambitions, low fossil fuels	28-40%	22-38%	22-35%	2-15%	0%	3-4%
		D	Decarbonization by 2050, low biofuels	0%	0%	92-96%	0-1%	0-45%	3-4%
		E	Decarbonization by 2050, low efuels	0%	0%	34-70%	24-35%	0%	3-4%
		F	Decarbonization by 2050, low fossil fuels	0%	0%	41-80%	16-54%	0%	3-4%
[41]	DNV model	-	-	35%	20%	40%			5%
[50]	Global vessel fleet model	Package 1	SSP2, RCP2.6| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	12%	10%	0%	78%	0%	0%
		Package 2	SSP2, RCP2.6| Biofuels from 2025, 20% speed cut	1%	1%	98%	0%	0%	0%
		Package 3	SSP2, RCP2.6| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	10%	1%	49%	20%	20%	0%
[43](for 2035)	ITF International freight model	-	80% carbon reduction factor, carbon pricing to reach 500 US$/tonne by 2035	2%	3%	25%	70%	0%	0%
[58]	-	-	-	28%	14%	0%	42%	26%	0%
[59] & [51]	GloTraM model	BAU	No carbon budget, RCP2.6, SSP3, all fuels excluding hydrogen	75%	22%	3%	0%	0%	0%
		Scenario 1	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, low bio	38%	16%	3%	43%	0%	0%
		Scenario 2	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, high-bio	38%	6%	21%	35%	0%	0%
		Scenario 3	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 50% out-sector offsets, high bio	58%	29%	13%	0%	0%	0%
[60]	SEAMAPS model	A	200 $/tCO2eq, 30% fuel saving assumption	3%	4%	0%	89%	4%	0%
		B	480 $/tCO2eq, 30% fuel saving assumption	0%	0%	0%	92%	8%	0%
		C	780 $/tCO2eq, 70% fuel saving assumption	0%	0%	0%	98%	2%	0%
[61]	IAM - COFFEE	NDC,C1000,C600	Ranges of scenarios: Nationally Determined Contributions (NDC), 1000 and 600 GtonCO2 carbon budget until 2100	48-61%	1-52%	0-29%	0-11%	0%	0%
	IAM - IMACLIM-R			52-75%	0%	25-45%	0-3%	0%	0%
	IAM - IMAGE			72-89%	0%	11-28%	0%	0%	0%
	IAM - PROMETHEUS			13-89%	4-6%	6-58%	0-11%	0-12%	0-2%
	IAM - TIAM-UCL			41-91%	9-41%	0-3%	0-15%	0%	0%
	IAM - WITCH			88-96%	0%	3-5%	3-7%	0%	0%

Table 2.3.: Summary of maritime shipping’s fuel mix forecasts in 2050.

Using the Global Transport Model (GloTraM) as its foundation, the study presented in [59] and [51] offers a detailed exploration of the maritime fuel landscape for 2050. GloTraM is a specialized simulation tool employed in the shipping industry to investigate future scenarios. This model is particularly adept at estimating CO_2 emissions by combining various modeling techniques, focusing on fleet evolution up to 2050. At its core, GloTraM operates by modeling the profit maximization of shipowners under macroeconomic, market, and regulatory scenarios. It uses a range of assumptions regarding the availability of different fuels, machinery, and technologies. The study spans various scenarios, from the "BAU" where traditional Oil-based fuels remain dominant at 75%, and LNG accounts for 22%, to "Scenario 3", which forecasts a significant shift with 58% Oil-based, 29% LNG, and an introduction of Biofuels at 13%. The study highlights how carbon budget, fuel viability, and biomass availability shape the maritime fuel mix.

Another more recent study by [62] used the GloTraM model. Providing two scenarios of decarbonization by 2050 and decarbonization by 2070, they suggest that the fuel mix will be dominated by ammonia. Detailed assumptions of recent scenarios remain undisclosed.

[41]'s projection sketched a potential fuel mix for maritime shipping by 2050. However, the backdrop or narratives guiding these projections remain undisclosed. As per this forecast, biofuels emerge as significant players, constituting 40% of the fuel mix. Oil-based fuels and LNG are projected to contribute 35% and 20%, respectively. DNV's 2018 outlook underlines the maritime industry's inclination towards biofuels while still retaining a significant dependency on established fuels.

In [49], they delved into the potential maritime fuel mix using their model. The study presented 24 scenarios, which were grouped into six primary sets, each illustrating a unique fuel mix outlook for 2050. Scenarios "A", "B", and "C" align with the previous targets set by the IMO in 2018. Specifically, "Scenario A" assumes a low cost for biofuels, projecting oil-based fuels to constitute between 32% and 38%, LNG ranging from 20% to 29%, and biofuels capturing 33% to 43% of the mix. Other fuels such as ammonia, hydrogen, methanol, and electricity have minor roles, with their contributions hovering between a negligible amount and a modest 4%. "Scenario B", which assumes a low cost for electro-fuels, foresees a diverse fuel mix. In this scenario, oil-based fuels are projected to account for 34-39%, LNG for 19-26%, and biofuels could vary dramatically from 0% up to 38%. Ammonia and hydrogen also hold a presence, ranging from 3% to 14%. "Scenario C", emphasizing a low cost for blue ammonia, offers a different trajectory, with specific details reflecting its unique assumptions. Conversely, Scenarios "D", "E", and "F" pivot towards the ambitious goal of full sector decarbonization by 2050.

"Scenario D," echoing the assumptions of "Scenario A," anticipates a low cost for biofuels. Similarly, "Scenario E" mirrors "B" but places its bet on the low cost of electro-fuels, and "Scenario F" parallels "C", spotlighting the low cost of blue ammonia. DNV's insights from 2022 illuminate the maritime industry's capacity for adaptability, with each scenario underscoring the different avenues the sector could take.

[50] used the Global vessel fleet model, which proposes a range of scenarios for the maritime fuel mix by 2050. Horton's methodology incorporated base year inputs from Clarkson and MRV, deploying three demand scenarios as defined by the IMO to model changes in the fleet, emission impacts, and cost implications. However, the specifics of the modeling approach and framework remain undisclosed. A feature of the "Package 1" scenario is its substantial reliance on ammonia and hydrogen, contributing a dominant 78% to the mix. In contrast, "Package 2" foresees a maritime industry powered by biofuels at 98%. Meanwhile, "Package 3" provides a more diversified outlook, showing significant contributions from biofuels, oil-based fuels, and a combination of ammonia and methanol. Gareth Horton's projections reveal the maritime industry's potential tilt towards alternative fuels, influenced by varying technology assumptions.

[60] utilizes a least-cost optimization model (SEAMAPS model) to evaluate the maritime industry's transition with different carbon tax scenarios. It integrates detailed fuel emission profiles, green fuel production costs, production capacity scaling, biomass availability, and climate action measures like carbon pricing and fuel demand reduction. The research identifies methanol and ammonia, produced via green hydrogen, as key to the sector's green transition, contingent on substantial upscaling of electrolyzer capacities. The analysis, based on well-to-wake emissions and including life-cycle fuel production costs, reveals the potential for significant emission reductions through adopting green fuels, particularly green ammonia, under high carbon pricing scenarios. The study's main limitations are the pure assumptions on fuel cost trajectories, biomass resource availability, and the pace of technological advancements.

The 2022 projections by the [58], albeit lacking detailed scenario narratives, suggest a maritime fuel landscape by 2050 where ammonia and methanol scale up as the primary contributors.

[61] aggregates 6 IAMs to run three sets of scenarios, ranging from Nationally Determined Contributions (NDC) to carbon-budget scenarios that limit global carbon emissions by 1000 and 600 GTonCO_2 by the end of the century. The paper uses the strength of a multi-IAM analysis of

international shipping, showing different scenarios as a result of models. Despite a shared goal, models show variability in predicting the energy future of shipping, influenced by different fuel options and structural trends, such as the shift towards electrification. The study suggests that a diverse portfolio of alternative fuels is crucial for developing green corridors. However, Electricity and methanol are not included in the predicted fuel mix across all models and scenarios, except for the Prometheus model. Additionally, oil remains part of the mix even in mitigated scenarios, with the extent of its use depending on each model's structure, in which models allow carbon capture technologies to offset the predicted emissions from shipping.

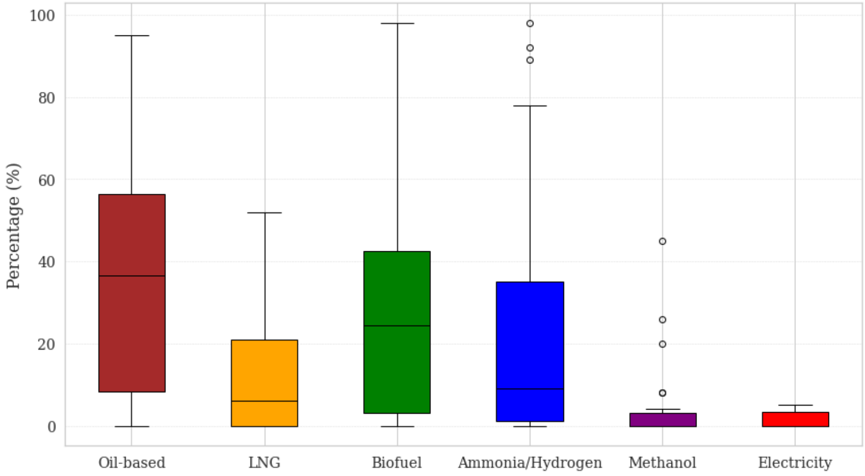


Figure 2.4.: Summary of global fuel share of different types of marine fuels with uncertainties in 2050.

From the knowledge gained from projections [Figure 2.4], electricity, despite its sustainable appeal, is not projected to be a primary fuel source for maritime shipping. This is mainly due to energy density and the battery-powered vessels' range limitation. Energy density constraints and refueling considerations impact the feasibility of battery-powered vessels for long-haul shipping [63]. The projections for hydrogen, ammonia, and biofuels exhibit high variability, emphasizing the existing uncertainty surrounding their adoption. Also, oil-based fuels seem to be present in most of the results, emphasizing the challenge of complete elimination of them. Interestingly, none of the reviewed reports or studies provided regional breakdowns for their fuel mix projections. Those that did offer predictions often lacked robust backing for their estimates, with results mainly driven by predefined scenarios such as high biofuel, low biofuel, low electro, etc.

2.3.3. EMISSION SIDE

Projected emissions are mostly derived from demand and supply forecasts, where demand drivers and the models estimate future demand which has to be met by fuel supply, and the resulting fuel mix, combined with emission intensities and energy efficiency, determines sector-specific emissions. The maritime sector is changing its approach to emissions, influenced by the IMO's new target. The IMO's revised ambitions are clear: a reduction in sector emissions by 20% (with aspirations of reaching a 30% cut) by 2030, culminating in full decarbonization by 2050. These goals stand in contrast to the earlier IMO target, which aimed for a halving of emissions, targeting a value of less than 0.40 Gt CO_2eq/year by 2050.

Table 2.4 presents and summarizes the estimated CO_2 emissions for the years 2030 and 2050. It also contains scenarios depicting those values with the corresponding description.

Source	Tool	Scenario	Description	Forecasted CO_2 emission ($GtCO_2$/year)	
				2030	2050
[18]	IAM (IMAGE)	SSP1	Sustainability - Rapid and sustainable economic growth, low inequality, and low population growth	-	1.2 - 1.6
		SSP2	Middle of the Road - Moderate economic growth, medium inequality, and medium population growth	-	1.2 - 1.7
		SSP2-mit	Climate policy scenario: This scenario assumes that a global climate policy is implemented	-	1 - 1.4
		SSP3	Regional Rivalry - Uneven economic growth, high inequality, and declining population growth	-	0.8 - 1.2
		SSP4	Inequality - High economic growth, high inequality, and declining population growth	-	1.2 - 1.6
		SSP5	Fossil-fueled Development - High economic growth, high inequality, and high population growth	-	2 - 2.6
[50]	Global vessel fleet model (Sectoral)	Package 1, low	SSP4, RCP6.0| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	0.5	0.18
		Package 1, central	SSP2, RCP2.6| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	0.58	0.19
		Package 1, high	SSP1, RCP4.5| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	0.6	0.2
		Package 2, low	SSP4, RCP6.0| Biofuels from 2025, 20% speed cut	0.62	0.6
		Package 2, central	SSP2, RCP2.6| Biofuels from 2025, 20% speed cut	0.79	0.81
		Package 2, high	SSP1, RCP4.5| Biofuels from 2025, 20% speed cut	0.82	1.1
		Package 3, low	SSP4, RCP6.0| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	0.5	0.2
		Package 3, central	SSP2, RCP2.6| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	0.59	0.3
		Package 3, high	SSP1, RCP4.5| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	0.61	0.48
[43]	International freight model (IFM)	Baseline	No additional measures beyond current	1.1	-
		Adjusted demand	50% coal trade reduction, 33% oil trade reduction	0.85	-
		Ultra-slow operation	Maximum speed reduction and technical measures.	0.18	-
		Low-carbon technology	Technical measures and low-carbon fuels	0.14	-
		Zero-carbon technology	Moderate speed reduction, technical measures, electric ships	0.07	-
		Maximum intervention	Max speed reduction, technical/operational measures, zero-carbon fuels	0.05	-
[44]	Regression analysis	TS1	Very low emissions, low sulfur, aggressive NOx cut, advanced tech, 90% NOx reduction by 2050	1.1	1.1
		TS2	Moderate emissions, low sulfur, moderate NOx cut, partial tech adoption	1.15	1.2
		TS3	Complies with IMO, high sulfur, standard NOx cuts, current tech standards	1.3	1.4
		TS4	Maintains current standard, high sulfur, standard NOx cuts, no shift to alternative fuels	1.4	1.5
[64]	Sectoral gravity model	BES	Base Energy Scenario (BES): continuation of current energy policies, a 2050 energy demand of 12.4 EJ	0.82	0.92
		PES	Planned Energy Scenario (PES): nations' current energy plans, Paris Agreement NDCs, 2050 energy demand of 11.8 EJ	0.75	0.75
		TES	Transforming Energy Scenario (TES): more ambitious energy policies with a shift towards renewables, 2050 energy demand of 9.5EJ	0.62	0.38
		IRENA 1.5C	IRENA 1.5°C Scenario Paris Agreement's 1.5°C goal, a comprehensive energy shift, 2050 energy demand of 7.9EJ	0.55	0.14
[65]	DNV model	Scenario 1	No policies lead to 2050 gains offset by shifted emissions, echoing fossil fuels.	1	0.83
		Scenario 2	GHG standards usher in carbon-neutral shipping, aiming beyond 80% emission reduction.	0.98	0.2
[49]	DNV model	IMO ambition (old)	ETS allowance 22 to 135 \$/tCO_2, CII and EEXI requirement: 40% to 75% reduction (2030 and 2050)	0.78	0.42
		Decarbonization2050	ETS allowance 14 to 250 \$/tCO_2, CII and EEXI requirement: 40% to 100% reduction (2030 and 2050)	0.78	0
[3]	IEA pathways	Technology Scenario	Focuses on tech solutions for energy demand and decarbonization	1	1.42
		2DS	Aims for a max 2°C global temperature rise by 2100 through energy system overhauls and increased renewables	0.8	0.64
		WB2DS	Targets temperatures Well Below 2°C, urging aggressive measures, rapid sector transitions, and robust policies	0.76	0.4
[4]	IAMs + Regression analysis	SSP2_RCP1.9_G	GDP and population projections based on SSP2, RCP2.6, Gravity model coupled with IAM	1.04	1.05
		SSP2_RCP2.6_L	GDP and population projections based on SSP2, RCP2.6, logistic model coupled with IAM	1.15	1.46
		SSP4_RCP2.6_G	GDP and population projections based on SSP4, RCP2.6, Gravity model coupled with IAM	1.03	1.04
		SSP4_RCP2.6_L	GDP and population projections based on SSP4, RCP2.6, logistic model coupled with IAM	1.19	1.47
		SSP5_RCP6.0_G	GDP and population projections based on SSP5, RCP6.0, Gravity model coupled with IAM	1.19	1.47
		SSP5_RCP6.0_L	GDP and population projections based on SSP5, RCP6.0, logistic model coupled with IAM	1.38	2.34
		OECD_RCP4.5_G	GDP and population projections based on OECD, RCP4.5, Gravity model coupled with IAM	1	1.14
		OECD_RCP4.5_L	GDP and population projections based on OECD, RCP4.5, logistic model coupled with IAM	1.12	1.37
[66]	Monte Carlo simulation technique (Sectoral)	Gray	Baseline scenario	1.6	2
		Blue	Incorporating nuclear, biofuel, LNG, and technical/operational measures	0.9	0.6
		Yellow	CO_2 reduction potential is like the blue line but excludes nuclear	1.1	0.9
[67] & [51]	GloTraM model (Sectoral)	BAU	No carbon budget, RCP2.6, SSP3, all fuels excluding hydrogen	1.05	1.4
		Scenario 1	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, low bio	1	0.7
		Scenario 2	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, high-bio	0.9	0.59
		Scenario 3	Carbon budget 33Gt, RCP2.6, SSP3, all fuels excluding hydrogen, 50% out-sector offsets, high bio	0.85	1
[17]	IAM (IMAGE)	BAU	Baseline scenario	0.75	0.8
	IAM (IMAGE)	Mitigated	2C degree by 2100 scenario	0.62	0.35
	IAM (POLES)	BAU	Baseline scenario	1.2	1.5
	IAM (POLES)	Mitigated	2C degree by 2100 scenario	0.75	0.48
	IAM (MESSAGE)	BAU	Baseline scenario	1.2	1.5
	IAM (MESSAGE)	Mitigated	2C degree by 2100 scenario	0.75	0.48
[68]	Shipping fleet turnover model	Baseline with EEDI standards	Improves new ship efficiency by 15% by 2015, 20% by 2020, and 30% by 2025 from their 2005 levels	1.15	1.45
		Additional technology	Technology 20% co2 reduction (1.5%/year) from 2025 through 2040	1.1	1.3
		Operational and new ship technology efficiency	Technology 20% co2 reduction (1.5%/year) from 2025 through 2040 operational 20% co2 reduction (1.1%/year) 2015 through 2035	0.9	0.9
		Top 5% industry efficiency leader	Fleet-wide 54% gco2-per-tonne-nm intensity reduction from 2015 to 2035 (3.8%/year) to match 5% highest efficiency cargo-hauling ships in 2011	0.8	0.82

Table 2.4.: Summary of maritime shipping's emission forecasts in the future.

The research by [18] utilizes the IAM (IMAGE) tool to forecast CO_2 emissions by 2050 across various SSPs, which have been explained earlier. For the SSP1 scenario, CO_2 emissions are projected to be in the range of 1.2 to 1.6 $GtCO_2$/year by 2050. The SSP2 scenario anticipates emissions between 1.2 and 1.7 $GtCO_2$/year. The SSP2-mit scenario, emphasizing global cooperation to achieve the Paris Agreement's objectives, projects a more optimistic range of emissions between 1 and 1.4 $GtCO_2$/year. In contrast, the SSP3 scenario expects emissions between 0.8 and 1.2 $GtCO_2$/year, while the SSP4 scenario projects emissions between 1.2 and 1.6 $GtCO_2$/year. The SSP5 scenario is the most concerning, forecasting the highest emissions between 2 and 2.6 $GtCO_2$/year. The variance in projected emissions across these scenarios highlights the significant impact of socioeconomic factors, policy decisions, and technological pathways on the future of marine-related CO_2 emissions.

In a detailed study by [50], various potential futures for marine CO_2 emissions were presented using the Global vessel fleet model. Horton grouped his predictions into three main categories. The first set of predictions highlights a move from using grey to green hydrogen, with an introduction of ammonia and hydrogen as marine fuels starting in 2025. Additionally, this group anticipates electric ships for shorter routes by 2045. The second group centers on using biofuels from 2025 and suggests ships could reduce their speed by 20% to cut emissions. The third category, termed the "high-tech" approach, expects ships to start using ammonia and methanol by 2025, with a gradual switch from grey to green hydrogen after 2040. Importantly, Horton's data indicates that early use of alternative fuels and electrification can lead to the lowest emissions, with figures dropping to as low as 0.18 $GtCO_2$/year by 2050 in some scenarios. On the other hand, scenarios heavily reliant on biofuels without additional changes could result in the highest emissions, reaching up to 1.1 $GtCO_2$/year by 2050. This study underscores the significant impact of our fuel choices and technological shifts on future marine emissions. One shortcoming is that most of the influential parameters are fixed exogenously throughout the estimations.

In the study by [43], the potential futures of marine CO_2 emissions were explored using the ITF International freight model. The scenarios presented span a spectrum of interventions, from maintaining the status quo to aggressive emission reduction strategies. The "Baseline" scenario, which lacks additional measures, projects CO_2 emissions at 1.1 $GtCO_2$/year by 2050. The "Adjusted demand" scenario, which factors in reductions in coal and oil trade, predicts a slightly lower emission of 0.85 $GtCO_2$/year. The introduction of ultra-slow operations and low-carbon technologies further reduces the projected emissions to 0.18 and 0.14 $GtCO_2$/year, respectively. Notably, the "Zero-carbon technology" scenario, which merges speed reduction and alternative fuels, forecasts a substantial drop to 0.07 $GtCO_2$/year. The most assertive approach, the "Maximum intervention" scenario, anticipates the lowest emissions at 0.05 $GtCO_2$/year. This research underscores the significance of technological and operational shifts in reducing marine CO_2 emissions and emphasizes the potential of aggressive interventions.

In the work by [44], marine CO_2 emissions were forecasted using a linear regression analysis approach, leading to four distinct scenarios. The TS1 scenario, characterized by very low emissions and aggressive controls on nitrogen oxides (NOx), projects emissions to remain stable at 1.1 $GtCO_2$/year from 2030 to 2050. TS2, which assumes moderate emissions and NOx controls, anticipates a slight increase from 1.15 $GtCO_2$/year in 2030 to 1.2 $GtCO_2$/year by 2050. The TS3 scenario, aligned with the old IMO efficiency standards, forecasts emissions to rise from 1.3 $GtCO_2$/year in 2030 to 1.4 $GtCO_2$/year in 2050. Lastly, the TS4 scenario, which retains current emission standards, predicts a steady ascent from 1.4 $GtCO_2$/year in 2030 to 1.5 $GtCO_2$/year by 2050. The projections serve as a reminder of the environmental implications of regulatory choices and emphasize the need for stricter emission controls.

In the detailed analysis by [64] using the Sectoral model, a variety of scenarios were presented, each reflecting a different trajectory of marine CO_2 emissions. The Base Energy Scenario (BES) portrays a future where current trends persist, leading to emissions of 0.92 $GtCO_2$/year by 2050. The Planned Energy Scenario (PES), in contrast, embodies the current energy and climate commitments of nations, predicting a stabilization of emissions at 0.75 $GtCO_2$/year by 2050. The Transforming Energy Scenario (TES) offers a more optimistic outlook, emphasizing a shift towards a sustainable energy future and forecasting a reduction to 0.38 $GtCO_2$/year by 2050. Perhaps the most ambitious of all, the IRENA $1.5^{\circ}C$ Scenario is geared towards meeting the Paris Agreement's stringent $1.5^{\circ}C$. This scenario projects a significant reduction in marine CO_2 emissions to 0.14 $GtCO_2$/year by 2050. IRENA's 2021 findings underscore the potential of policy decisions and energy transformations in reducing marine CO_2 emissions.

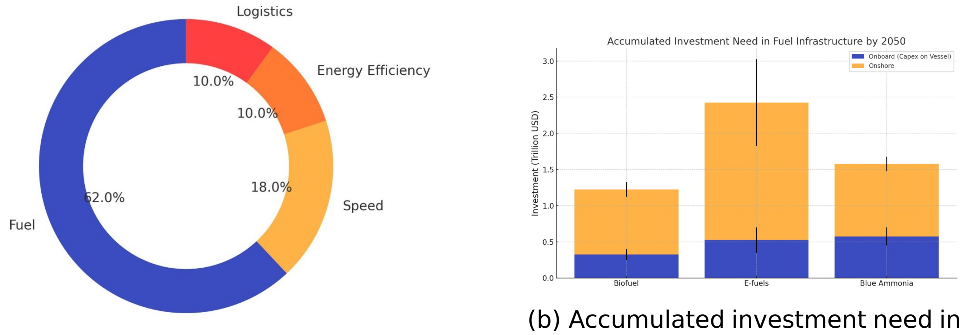
In the [49], two groups of scenarios are presented. The "IMO ambition (old)" scenario, which considers a range of ETS allowances and the implementation of CII and EEXI regulations, forecasts a CO_2 emission reduction to 0.42 $GtCO_2$/year by 2050. The "Decarbonization2050" scenario embraces a more aggressive ETS allowance range and the same regulations. This scenario is geared towards the new IMO target, aiming for a complete decarbonization of the maritime sector by 2050. The predicted emissions are zero by 2050, showcasing the sector's potential to fully align with global climate goals. DNV's findings offer a compelling case for aggressive policy interventions and technological innovations.

By looking closer at requirements leading to the full-decarbonized projections of [49] suggest a dominant role for biofuels, spanning 32% to 96% of the fuel mix, with blue and green ammonia contributing up to 65% and 55% respectively. Electric propulsion, though still emergent, is anticipated to account for 3-4% of the mix. To actualize these configurations, significant financial commitments are necessary, with vessel-specific capex for biofuels, e-fuels, and blue ammonia estimated between \$0.25-\$0.7 trillion and onshore requirements reaching up to \$2.5 trillion. Regulatory standards, such as the EEDI's ambitious 90% reduction target by 2040 and the ETS's escalating allowance prices. These requirements are shown in Figure 2.5. The approach to locking in the target and finding requirements to reach it is highly commendable. However, among these projections lies a high degree of uncertainty, exacerbated by the inherent limitations of sectoral modeling and its vulnerability to externalities. Notably, the specific assumptions driving DNV's model remain undisclosed, masking key variables and considerations.

A more recent study by DNV, [65], presents two contrasting scenarios for marine CO_2 emissions. These scenarios are not new but are reruns of two individual scenarios DNV previously published in 2022. The first scenario predicts a future where the absence of new policies leads to a modest reduction in emissions by 2050, dropping to 0.83 $GtCO_2$/year. A shift towards higher-emission fuels largely offsets this reduction. In contrast, "Scenario 2" envisions a world where stringent greenhouse gas standards facilitate the transition to carbon-neutral shipping. This transition results in a reduction in CO_2 emissions, dropping to a mere 0.2 $GtCO_2$/year by 2050.

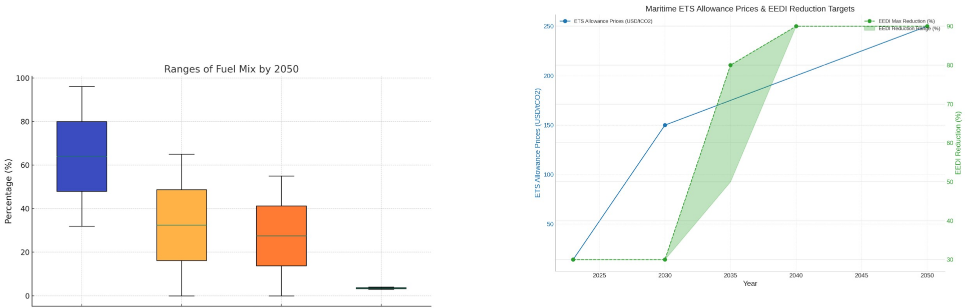
[3] offers a comprehensive look into the future of marine CO_2 emissions through various scenarios. The "Technology Scenario" emphasizes technological solutions, projecting emissions of 1.42 $GtCO_2$/year by 2050. The "2 Degree Scenario (2DS)" outlines a future where global warming is limited to 2°C, with CO_2 emissions decreasing to 0.64 $GtCO_2$/year by 2050. The most assertive of the three, the "Well Below 2 Degree Scenario (WB2DS)", envisions a future where global temperatures are kept well below a $2^\circ C$ rise, resulting in a more significant reduction in emissions to 0.4 $GtCO_2$/year by 2050. The projections from IEA 2017 illuminate the role of technological innovations and aggressive policy interventions in curbing marine CO_2 emissions.

In [4, p. 236], a range of scenarios were presented to provide insights into the potential trajectories of marine CO_2 emissions. These scenarios, developed using integrated assessment models combined with gravity



(a) Emission reduction contribution.

(b) Accumulated investment need in fuel infrastructure.



(c) Range of fuel mix

(d) Maritime ETS allowance prices and EEDI reduction targets.

Figure 2.5.: Conditions under which full decarbonization is reached based on DNV2022 scenarios.

and logistic curves, capture different outcomes based on SSPs and Representative Concentration Pathways (RCPs). Among 24 scenarios produced by the study, 8 of them were chosen. The rationale behind it was explained earlier in the demand section. The SSP-based scenarios project emissions ranging from 1.04 to 2.34 $GtCO_2$/year by 2050, while the OECD-focused scenarios anticipate figures between 1.14 and 1.37 $GtCO_2$/year for the same year. The variations in emission forecasts stem from differing projections of transport work. These variations are, in turn, a result of different socio-economic projections and distinct methods used to determine the relationship between transport work and independent factors such as per capita GDP, population, and primary energy demand. This analysis by the IMO provides a deep understanding of the maritime sector's potential CO_2 emissions in Business-as-usual scenarios, emphasizing the importance of socioeconomic trajectories in shaping the sector's future. The variance in results is also partially due to the modeling approach.

[66] study delivers a variety of scenarios, each showcasing unique marine CO_2 emission trajectories. These scenarios are devised using the Monte Carlo simulation, a computational method that employs random sampling to model intricate systems. By generating numerous random samples based on input variable probability distributions, it estimates the output variable's probable distribution. This technique is prevalent in multiple domains, like finance and engineering, especially when modeling complex systems. The "Gray" variant serves as the baseline, depicting the highest emissions of 2 $GtCO_2$/year by 2050. In contrast, the "Blue" scenario, emphasizing technological innovations and a shift towards alternative fuels like nuclear, biofuel, and LNG, forecasts significantly lower emissions of 0.6 $GtCO_2$/year by 2050. The "Yellow" scenario offers a similar CO_2 reduction potential to the "Blue" one, albeit through different strategies, and predicts emissions of 0.9 $GtCO_2$/year by 2050. These scenarios underscore the significant variability in potential future emissions, hinging on technological, policy, and strategic choices. The study reinforces the message that proactive measures can lead to substantial emission reductions, while inaction could result in the opposite.

Utilizing a global fleet turnover model, [68] estimates shipping emissions by assessing the impact of enhanced efficiency from 2020 to 2050, considering factors such as fleet characteristics and operational data. They calibrated ship population against IMO projections and examined the influence of vessel age, size, and technology on carbon intensity. The scenarios include a baseline with EEDI standards, further technological enhancements (EEDI+), and industry-leading efficiency practices, each providing a differing scale of emission reductions. By 2030, adopting top efficiency practices could significantly reduce CO_2 emissions and oil consumption. By 2050, the model suggests that emissions could stabilize at current levels despite increased activity, underscoring the effectiveness of operational improvements and advanced technologies in mitigating shipping's carbon footprint. The study provides a detailed analysis of potential reductions in carbon emissions in the maritime sector, demonstrating the substantial benefits of efficiency measures while also implicitly acknowledging the challenges of implementing such changes industry-wide. The study's assumptions might not accurately reflect fluctuations in scrappage rates and shipping activity while downplaying the socio-economic, regulatory, and geopolitical factors affecting shipping efficiency. Economic considerations, such as costs and investments for efficiency improvements, are not fully addressed, and the projections may be overly optimistic about the industry's readiness to embrace new technologies.

The [59] and [51] studies, employing the GloTraM model, offer a series of scenarios with varied perspectives on the potential marine CO_2 emissions. The "Business As Usual (BAU)" scenario, which does not restrict the carbon budget and excludes hydrogen from its fuel mix, anticipates emissions of 1.4 $GtCO_2$/year by 2050. "Scenario 1" and "Scenario 2" share similar carbon budget and temperature rise assumptions yet differ slightly in their projections, with emissions forecasted at 0.7 and 0.59 $GtCO_2$/year, respectively, by 2050. "Scenario 3", although aligned with the carbon budget and pathway of the previous two, includes a huge out-of-sector offsetting potential with the exclusion of hydrogen, resulting in an emission projection of 1 $GtCO_2$/year by 2050. This range of scenarios emphasizes the sensitivity of marine CO_2 emission projections to fuel choices and out-of-sector offsetting potential.

A report by the PBL Netherlands Environmental Assessment Agency [17], collects a series of Integrated Assessment Models (IAMs) to project potential marine CO_2 emissions. Three distinct models - IMAGE, POLES, and MESSAGE - are utilized, with each model having unique structures and underlying assumptions. Each model offers two scenarios: a baseline (BAU) and a mitigated scenario that aims for a 2°C temperature rise cap by 2100. The BAU scenarios present forecasts ranging from 0.8 to 1.5 $GtCO_2$/year by 2050. In contrast, the mitigated scenarios, aligned with global climate targets, anticipate CO_2 emissions between 0.35 and 0.48 $GtCO_2$/year by 2050. The variance in projections between the models is largely attributed to their distinct structures and the assumptions they're based upon. The study also emphasizes the importance of understanding the distinctions and complexities of different modeling approaches when interpreting and comparing results.

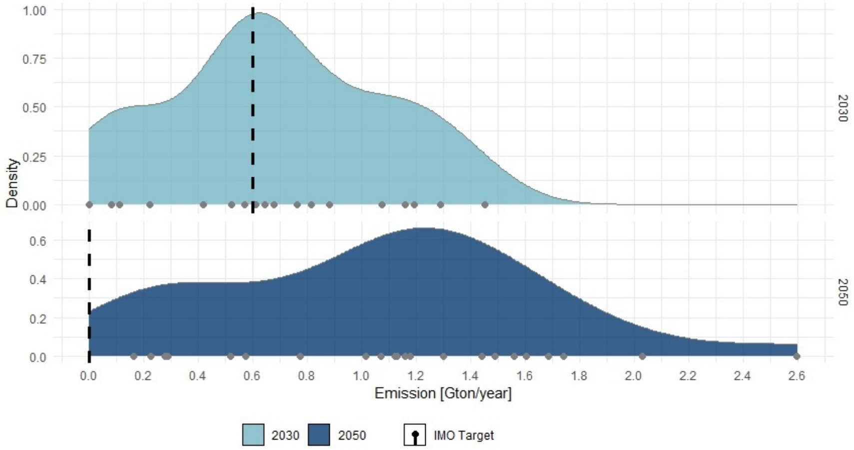


Figure 2.6.: Maritime shipping's CO_2 emission forecasts in 2030 and 2050 and the comparison to IMO's current target

Figure 2.6 illustrates the emissions projections for international shipping in 2030 and 2050, with each point representing a scenario of each study's findings. In 2030, projections tend to converge below the 1 $GtCO_2$/year mark, with multiple scenarios reaching the targets. However, the new IMO target for 2050 proposes a more ambitious reduction than most studies currently predict. By 2050, the dispersion of data points indicates even greater uncertainty, with the new IMO target appearing as an outlier well below the bulk of projections, reflecting a target that may be difficult to achieve under current trajectories. Therefore a change in the philosophy of looking at the problem is required. Instead of estimating the effects of individual measures and policies, we should set the target as clear as it is and find feasible pathways toward reaching it. An extensive approach is needed that combines modeling techniques, socioeconomic trends, fuel and tech shifts, regulations, and economic factors, ensuring alignment with global climate targets and contributing to climate action under Sustainable Development Goal 13 [69].

2.3.4. ASSUMPTIONS OVERVIEW

Before discussing the types of models, the key assumptions behind the presented output are reviewed. From this overview, it is clear that many were relevant but were overtaken by events, and a more robust approach may be required in this respect as well. In general, some assumptions remain valid, others are no longer valid, and others require dynamic updates before being used in a new model.

- Regarding the shipping demand:
  - The practice of using historical trends to predict the future by assuming the same trends is widely used in many studies. There is no better alternative, and this assumption would be maintained for now. This is done by most referenced studies. However, learning from recent disruptions, such as the financial crisis of 2008/09, the COVID-19 pandemic, and geopolitical trends, improves the accuracy of future predictions by accounting for potential volatility.
  - Pure assumptions about demand or fleet growth without empirical support possibly lead to lower reliability. Instead, models that incorporate a variety of economic and technical indicators to predict the trend of transport demand offer a more accurate approach. This could be enhanced further by various Machine Learning (ML) techniques.
  - The assumption that energy trade outcomes result merely from cost optimization overlooks the complexities of global trade flows.

  - Relying on a limited set of variables for demand prediction, such as GDP or consumption only, simplifies the prediction model. Using more predictive variables increases the model's reliability.
  - Using proxy ports to estimate regional distances has its merits. However, this approach requires regular updates to reflect the changing landscape of global shipping hubs. This will ensure capturing the most accurate average shipping haul between regions.
  - Models that incorporate exogenous factors or constraints on trade in a baseline without a detailed analytical foundation, such as a fossil fuel trade ban, could lead to less reliable results. These scenarios could be useful for assessing the extreme cases.
  - Assumptions regarding shipping demand reduction measures, such as speed reduction and efficiency improvement, are valid and provide insights into potential emissions reductions. However, they should be grounded in recent trends rather than speculations.

- Regarding the supplying fuel mix:
  - Assumptions regarding the availability of biomass and carbon capture and storage (CCS) adoption rates are seen as reasonable. Due to the existing high uncertainty, sensitivity analysis on them is valuable.
  - Predictions on fuel prices and capacities need to be grounded in recent data and trends, moving away from pure assumptions.
  - Pushing for or limiting a specific alternative fuel can be useful for sensitivity analysis. These assumptions must reflect ongoing technological and market developments.

- Regarding the policy implications:
  - Assumptions based on outdated IMO ambitions are not valid anymore. Updated targets should be used.
  - National policies, regulations, and trade agreements require updates to align with the latest targets and commitments.
  - Carbon pricing mechanisms (such as carbon pricing and carbon budget) and emissions trading systems should reflect current policy landscapes and economic conditions.

Finally, the utilization of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) scenarios offers a valid framework for modeling future pathways. However, these scenarios must be periodically updated to incorporate the latest scientific understanding and policy directions. [70] indicates an upcoming update on SSPs.

2.4. COMPARATIVE ANALYSIS OF METHODOLOGIES

Based on the projections of various studies and methodologies, there is a wide variety of projections and outcomes. Now, the general frameworks used to obtain those scenarios will be discussed to find the most qualified modeling framework for the context of this study. The studies and models reviewed in this paper can be categorized into five types: integrated modeling, sectoral modeling, regression analysis, life-cycle assessment, and undisclosed models in reports.

Integrated modeling takes a holistic approach, modeling interactions between various components, such as policy, technology, climate, and market forces. It helps understand complex interactions that affect emissions and explore different policy and technology options. Integrated assessment models (IAMs) have been widely used to explore the consequences of different long-term climate change mitigation strategies. These models provide a detailed representation of the world's energy, land use, agricultural, and climate systems, as well as their inter-linkages, cross-sectoral, and cross-regional connections over time. However, the level of uncertainty is high, and the results rely heavily on assumptions. The general limitation of integrated models is that they often operate at a high level of aggregation, which can mask sector-specific details such as the shipping sector. Two recent exceptions are [18] and [42], which expanded the maritime sector into the IMAGE and TIAM models, respectively. *Sectoral modeling* looks at the shipping sector, examining the interactions between different sub-sectors to identify factors. They can dive into deeper details of operational measures such as speed optimization, engine efficiency improvement, hauling and waiting time, and port management. However, they don't capture the whole economy and miss some crucial factors such as inter-sectoral and inter-regional spillovers. *Regression analysis* is a statistical method used to establish relationships between variables, like the impact of fuel prices and economic growth on shipping transport work demand. Its primary limitation is not capturing the inherent complexities of the system, and its application remains limited to shipping demand projection. Regression analysis can be coupled with other modeling techniques to make the study more consolidated like the work done by IMO fourth report that is referenced by many studies. *Life-cycle assessment* quantifies the environmental impacts of a product or system from production to disposal. It helps understand the full environmental impact of shipping, including indirect emissions from fuel and other inputs used in the sector. However, most of these assessments focus on one specific option's perspective, and most applications are on supplying the fuel side only. *Reports* are produced by specific organizations or institutions to summarize their findings on a particular topic. Reports are undisclosed, so the reliability of the results from an academic point of view remains unknown. However, given the reputation of the organizations behind the report, they are referenced by the sector's policymakers. Therefore, they are valuable despite the lack of knowledge of the underlying assumptions.

The quality of a model is its suitability for its purpose and objective. Each model is designed with a specific objective and purpose. Sectoral models focus on detailed analysis within a narrow domain, while integrated holistic models offer broader coverage but may lack depth in specific areas. According to the objectives and context of this study, we look for models that go into more depth on the shipping side but still take a holistic approach. To find the quality of existing literature in the context, five relevant criteria are defined and justified in the section 2.2. Table 2.5 shows the final average scores of each literature with its corresponding modeling method. A more detailed scoring table is also presented in the Table A.1. The insights provided by Table 2.5 can help to select the model direction for further research. Most of the studies are conducted by using a sectoral model. It also shows that integrated modeling has the highest average rate of 8.89, followed by undisclosed models within reports at 7.16. Both sectoral modeling and regression analysis have a rate of 7, while life-cycle assessment stands at 5.43. Figure 2.7 presents the number of studies analyzed with their corresponding average MCDA score. Therefore, due to having the required features, integrated modeling emerges as the most promising starting point for modeling international shipping pathways.

Table 2.5.: Publications and their average MCDA ratings.

N	Method	Literature	Average MCDA rate
6	Integrated modeling	[26], [42], [18], [61], [17], [4]	8.89
10	Sectoral modeling	[25], [41], [49], [65], [66], [59]/[51], [43], [50], [60]	7
2	Regression analysis	[45], [44]	7
6	Life-cycle assessment	[16], [10], [57], [56], [47], [21]	5.43
4	Undisclosed	[64], [3], [68], [58]	7.16

Integrated assessment models (IAMs) -the main integrated tools- are often used to develop and assess pathways in which greenhouse gas emissions are reduced, aiming to limit warming to specific temperature targets at the lowest overall cost [70]. Sectoral emission projections from these pathways can help policymakers in shaping their countries' climate targets. IAMs combine detailed models of energy system technologies

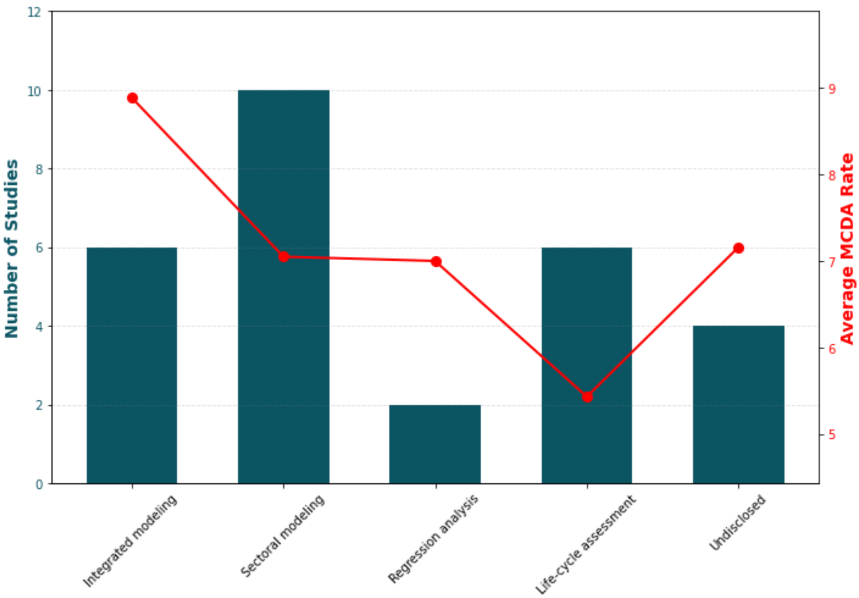


Figure 2.7.: Publications review: Number of studies vs Average MCDA rating.

with simplified economic and climate science models to evaluate different population, economic, and technological pathways. They enable an assessment of the feasibility of achieving specific climate change mitigation goals using different scenarios based on SSPs. These SSPs form the basis of key projections such as population, economies, and technology improvement rates developed by the International Institute for Applied Systems Analysis (IIASA) [40].

However, it's important to note that running scenarios in IAMs comes with the cost of time and complexity. Also, there are still gaps in IAMs, including the low level of representation of shipping. At the moment, international shipping is mostly underrepresented in most IAMs. Improving the representation of international transport would provide better insight into its potential contribution to global mitigation [17, 61]. Despite some recent improvements done by [18], [26], and [42], most of the models typically treat shipping demand as an exogenous variable and do not necessarily capture connections to other aspects of the global economy. Now we will take a closer look at the underlying assumptions and the capacity for improvement of studies that used IAMs.

[42] used the TIAM-UCL model to present world maritime trade scenarios in a 4°C future and a 2°C future. The article gives a good representation of the evolution of disaggregated trade demand in response to global climate change mitigation efforts. The paper also discusses the poten-

tial trade-offs that may arise as the shipping industry adapts to changing climates. However, the study focused only on the demand side and did not represent possible alternative fuels and their potential in the fuel mix. Also, the same neglection of cross-trade of energy commodities exists. Trade flow projections for these commodities are derived using the TIAM-UCL global energy system model. While optimization offers valuable insights, it also introduces a limitation by favoring future technological solutions rather than immediate demand-side changes. Additionally, despite the global scope of the study, the discussion of shipping distance is missing, and therefore, the trade demand remains in mass-based units rather than [mass × distance].

In [18], significant breakthroughs were achieved to deepen the integration of shipping into IMAGE IAM. They examine shipping activity demand under high global climate-mitigation scenarios. The discussion of inter-regional distances is evident, and the effects of different SSPs on shipping demand and renewable energy requirements are investigated. However, the article does not address alternative fuel mix and focuses only on the demand side. Additionally, the IMAGE model is a partial equilibrium simulation model with fewer macroeconomic details in the short term. Also, the trade in energy commodities such as oil, gas, and coal results from energy balance and the IAM's least-cost choice. This could lead to neglection of the cross-trade in which a region can be an exporter and importer in the same year, leading to underestimating the actual physical flow of trade.

[26] used the IAM BLUES model[71] to develop scenarios that considered different fuel alternatives, demand assumptions, and national mitigation targets, but the study examined only Brazil and not global shipping. There is potential to expand the scope of research to include international and global maritime shipping. Also, the demand for transport activity is given exogenously.

In the most recent work, [61] brings together multiple IAMs to conduct the first multi-IAM on the future of shipping from an integrated perspective. The study uses the current version of scenarios by COFFEE [72], IMACLIM-R [73], IMAGE [74, 75], PROMETHEUS [76], TIAM-UCL [77], and WITCH [78, 79] models. Effective models highlight the importance of diverse fuel alternatives and the influence of models' structure and underlying constraints on obtaining results. The authors conclude that an oversimplified view of shipping demand limits the study. These models often overlook significant factors, such as the influence of imperfect markets and rising geopolitical tensions, which can substantially affect global shipping dynamics and demand. Future studies could benefit from incorporating economic analyses, particularly regarding the impact of a carbon tax on international shipping.

In addition to the mentioned articles, two reports also included IAMs in their overviews.

A report by the PBL Netherlands Environmental Assessment Agency [17] draws on results from integrated assessment models such as POLES, MESSAGE, and IMAGE. The report gives valuable insight by using different models. The report recommends distinguishing between international and domestic shipping emissions, incorporating diverse fuels and efficiency standards, and offering distinct emissions reporting for the shipping sector as a direction for improving IAMs. Additionally, integrating sector-specific models with IAMs could improve the depiction of technological options within the shipping domain. According to the report, IAMs show potential in modeling international shipping emissions, yet there's a notable gap in the detail and prioritization of such reporting. While models like POLES demonstrate a detailed approach by integrating trade flows and efficiency metrics, others like MESSAGE, WITCH, and REMIND offer less detail, focusing merely on energy demand and emission factors. A multi-IAM analysis boosts the reliability of climate policy advice by contrasting model outcomes to highlight trends and differences. Given each model's different structures and assumptions, it assesses uncertainties and model sensitivities. Furthermore, multi-IAM analysis broadens scenario and policy option exploration, supporting stronger climate policy decisions. This will need the enhancement of shipping representation in multiple IAMs.

In [4, pp. 345–378] the methodology for projecting shipping emissions involves six steps: First, it projects transport work for non-energy products by linking historical maritime transport data to economic indicators like GDP and population, then forecasts future transport based on these relationships. Second, it estimates transport work for energy products using two regression models and coupling to multiple IAMs. Third, the study analyzes the 2018 fleet and its emissions by ship category. Fourth, it forecasts future fleet composition through literature review and stakeholder feedback. Fifth, it projects ships' future energy efficiency considering regulatory and market changes. Finally, it combines these elements to project shipping emissions. They investigate 24 scenarios in total, including high mitigation scenarios aligned with the Paris Agreement. Although the methodology of creating regression models and coupling them to IAMs for policy assessment is rigorous and innovative, there is room for improvement, especially in the energy commodities (oil, gas, and coal) trade. Two regression models are the non-linear logistic regression and the augmented gravity model with fixed effects. In the logistic model, the only variable used to predict the trade of energy cargo trade is the global consumption of that product. The second model, an augmented gravity model, provides an interesting approach but is constrained by its exclusive focus on GDP and population as predicting parameters and aggregating trade demand by ship types rather than specific cargoes. Adding more influential parameters such as regional consumption and production of both importer & exporter regions, and fuel price could improve the reliability of the model.

Modeling framework overview In the quest to identify the most appropriate modeling framework for charting a path to zero emissions in the international shipping sector by 2050, it's imperative to adopt a holistic approach that synergizes the strengths of various models while addressing their limitations. A list of the pros and cons of each model, considering the aim of this paper, is shown in Table 2.6.

Integrated Assessment Models (IAMs) are pivotal for their broad analysis of global energy, land use, and climate systems, facilitating an understanding of long-term climate change mitigation strategies across sectors and regions. However, IAMs' expansive scope often leads to a generalized treatment of the shipping sector, missing the intricate details of maritime operations and technologies. This high-level perspective is IAMs' primary drawback, as it overlooks the detailed specifics crucial for shipping. To counteract this shortfall, sectoral models are valuable to infuse the required granularity into the analysis. These models excel in detailing the operational aspects and technological details of the shipping industry, which IAMs gloss over. By integrating insights from sectoral models, the framework achieves a more comprehensive understanding of shipping dynamics, from fuel efficiency measures to vessel characteristics. Nevertheless, sectoral models typically focus on narrower aspects and might not fully capture the environmental impacts and specifics of various fuels over time—a gap effectively bridged by Life Cycle Assessment (LCA) methods. LCAs offer a detailed evaluation of fuel options' environmental footprint. However, they are limited by a singular focus on individual fuels without considering broader temporal dynamics. This is where the holistic view of IAMs complements LCAs by integrating these detailed environmental assessments into a broader temporal and systemic context. Regression models further enhance the framework by providing dynamic demand projections. They could incorporate a wide array of variables such as economic growth, population, shipping distances, fuel price, consumption, and production of cargo to predict trade flows. To increase the accuracy of such predictions, these predictions should be done bilaterally between regions and disaggregated for each cargo type. This approach will capture particular dynamics of each pair of importer-exporter regions, and each cargo type. However, regression models, with their focus on quantitative data, may overlook the qualitative aspects of policy impacts and market forces, elements that IAMs and sectoral models can capture.

This integrated approach of using IAMs for connecting sectors & regions and policy evaluations, sectoral models for detailed operational measures, LCAs for studying fuel impacts, and regression models for predicting demand mitigates the limitations of individual models and creates a robust, detailed, and coherent strategy that strengthens industry discussions and expert propositions. There are similarities and synergies between shipping and the aviation sector, and the same progress of integration perspective is taking place in the aviation sector [17, 80].

Method	**Pros**	**Cons**
Integrated modeling	Holistic approach; long-term assessment; policy analysis; inter-sectoral and global integration	Lack of sector-specific detail; sensitive to assumptions; high uncertainty
Sectoral modeling	Detailed sector-specific analysis; high specialization in operational measures, efficiency improvement, speed reduction measures, etc.	Limited scope beyond the sector; integration with broader assessments is complex
Regression analysis	Identifies trends/correlations; provides predictive insights based on historical data	Limited in capturing policy dimensions; data-intensive; risk of oversimplification
Life-cycle assessment	Comprehensive environmental impact assessment; details on a specific fuel pathway	Mostly focusing on one specific option's perspective; no long-term assessment

Table 2.6.: General Pros and Cons of each modeling framework.

2.5. CONCLUSION

Climate change represents a critical global challenge, and international maritime shipping plays an undeniable role. Despite the sector's high ambition to achieve full decarbonization by mid-century, there is no established pathway. Currently, several modeling techniques and literature are examining the sector's future. This paper aimed *to find a suitable way of modeling to assess feasible pathways to the zero-emission shipping sector*. This is done in two main steps. Firstly, by evaluating the existing projections of future international maritime shipping, including transport activity demand, efficiency improvement, fuel supply mix, and emissions, to identify the most probable ranges and the underlying assumptions leading to this uncertainty and scenario. Secondly, the paper assessed the quality of the literature based on five criteria: sectoral integration scope, dimensionality, technology range, geographical scope, and scenario evaluation. Based on these criteria, an integrated, all-sides-encompassing, multi-technology, global, and multi-scenario model is essential for exploring pathways to decarbonize international maritime shipping by 2050.

International shipping transport demand is projected to significantly increase, expected to rise by 50% by 2030 and 100-150% by 2050. This necessitates a critical shift in the sector's energy matrix, where the use of electricity is constrained by energy density issues and the limited operational range of battery-powered vessels. The adoption rates of hydrogen, ammonia, and biofuels are marked by considerable uncertainty, reflecting the variability in future utilization scenarios. Projections for CO_2 emissions reveal a wide range of outcomes, with estimates around 1 $GtCO_2$/year by 2030, diverging significantly to span from zero to 2.6 $GtCO_2$/year by 2050, thereby highlighting the sector's challenge in aligning with new International Maritime Organization (IMO) targets.

The examination of emission projections, as shown in Figure 2.6, revealed that a significant number of projections do not align with International Maritime Organization (IMO) targets. The suggestion of authors is a paradigm shift; to set the target and find pathways to achieve these goals, rather than focusing solely on the impacts of individual measures. This change in approach supports a more directed effort in modeling and policy development to ensure the maritime sector contributes effectively to global decarbonization objectives by achieving climate mitigation targets.

The evaluation of modeling assumptions for existing scenarios by 2050 shows a mix of valid and outdated assumptions alongside those needing updates. Relying on historical trends in demand projection remains a rough but valid assumption. Most referenced studies use it. Evaluating wider economic and sector-specific data to find historical trends improves the reliability and accuracy of this assumption. Assumptions regarding the supply of technologies like biomass availability and CCS adoption rates are seen as reasonable but require up-to-date insights to reflect technological and market realities. Policy assumptions, particularly regarding IMO targets and carbon pricing, must be revised to align with the latest international standards. The paper highlights the critical role of updated SSP and RCP scenarios in ensuring models are grounded in current scientific and policy contexts.
[61]

Regarding the modeling framework, lessons should be learned from previous efforts. The robust approach of coupling econometric regression models with Integrated Assessment Models (IAMs) as demonstrated by [4] is noteworthy, though the range of predicting variables is limited. [17] and [61] highlight the potential of IAMs and the importance of multi-IAM analysis, despite the scarcity of detailed shipping information in most IAMs. [18] and [42] stand out for incorporating a more detailed representation of shipping into the IMAGE and TIAM-UCL models, respectively. However, the modeling of energy trade in these works, being the outcome of energy optimization, might underestimate scenarios where a region can be both an importer and exporter of cargo within the same period. Additionally, the discussion on potential fuel mixes is absent in these studies. Thus, the future direction for modeling suggests enhancing econometric models for energy commodities and other cargo shipping demands by incorporating a broader set of predicting variables. A disaggregated approach to regions and cargo types increases the accuracy of outcomes. It is recommended to utilize insights from sectoral models to represent improvements in efficiency, capital expenditures (CAPEX), operational expenditures (OPEX), and performance of vessels and ports, along with speed reduction and other operational measures. Insights from Life Cycle Assessment (LCA) studies of alternative fuels should be used to model their production pathways, learning curves, and environmental impacts. These elements should then be implemented in multiple IAMs and synthesized with expert opinions, such as those from [65], to improve informed decision-making in the sector. The limitations of such an approach would be the need for substantial computational power and the requirement for readily accessible, detailed data.

2.6. MODELING LAYOUT

Note: This section is *not* part of the published article. It is included here to clarify the modeling layout used in the next chapter.

Building on the insights from the literature review, this thesis develops a consistent modeling framework for international shipping within the WITCH integrated assessment model. WITCH provides the system-wide structure needed to capture interactions between trade, energy supply, fuel competition, and climate policy. However, in its standard form, international shipping is represented in aggregate and does not account for differences in cargo composition, vessel types, or fuel pathways. The contributions of this thesis address these limitations in three steps, summarized in Figure 2.8.

First, *Chapter 3* develops a mass-based, cargo-disaggregated bilateral trade model that responds to income growth, oil price signals, and policy timing. This replaces the common practice of treating shipping demand as exogenous and allows trade flows to adjust endogenously when climate policies change.

Second, *Chapter 4* links projected trade volumes to vessel classes and ship size categories, converting ton-mile activity into energy demand and required fleet capacity. This establishes the operational bridge between trade activity and shipping energy requirements.

Third, *Chapters 5 and 6* integrate multiple propulsion configurations and fuel pathways (oil-based, biofuels, methanol, ammonia, hydrogen, and LNG) into WITCH’s energy system structure, allowing fuel competition and emissions outcomes to emerge from technological costs, resource availability, and policy constraints. Scenario analysis is conducted using explicit policy levers, including global carbon pricing, sector-specific fuel taxation, and fuel-specific ON/OFF switches that restrict or enable the deployment of fuels such as ammonia. The framework also tests the effect of adopting or delaying the IMO 2050 full decarbonization target and evaluates outcomes under net-zero-consistent transition pathways in line with the Net Zero Framework discussed at MEPC-83.

Together, these steps provide a coherent representation of the international shipping module in the WITCH model, enabling analysis of decarbonization pathways in which trade patterns, fleet evolution, fuel supply, and climate policy interact.

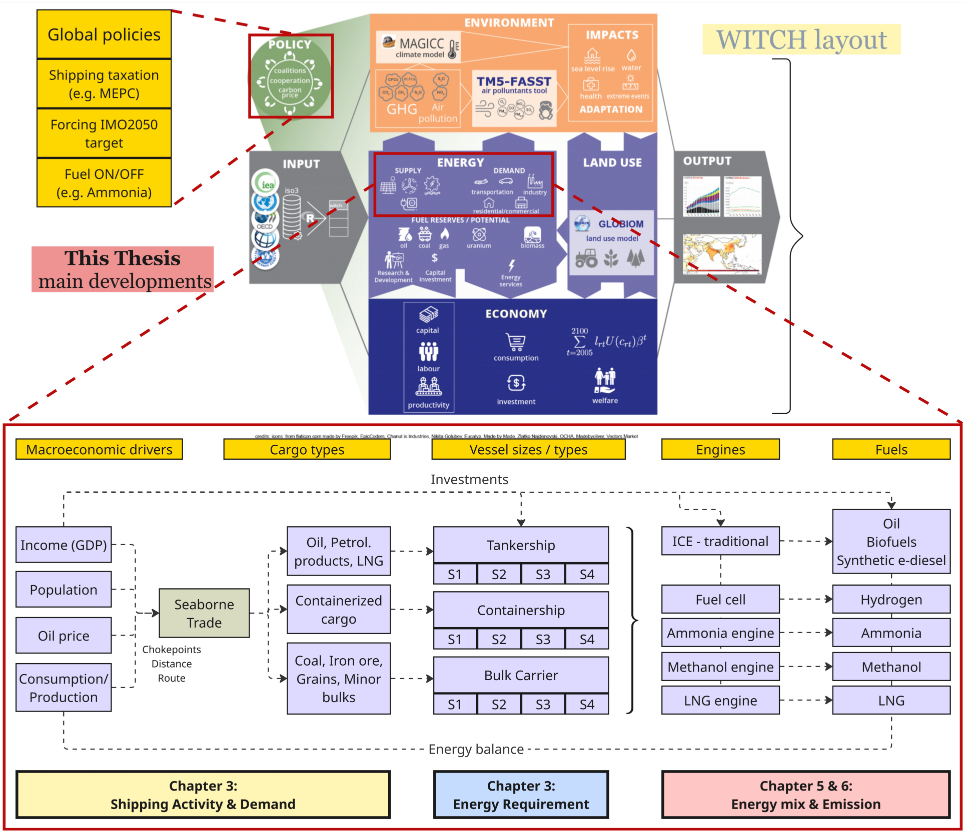


Figure 2.8.: Layout of WITCH IAM model and this thesis contribution.

3

SHIPPING ACTIVITY

This chapter develops a bilateral, cargo-specific representation of international shipping activity that is fully integrated into the global modeling framework. Building directly on the limitations identified in the literature review, it replaces exogenous assumptions about shipping demand with an econometric formulation that allows trade flows and transport activity to respond endogenously to economic growth, energy prices, and climate policy. In doing so, the chapter establishes the demand-side foundation needed to link global trade dynamics to energy use and emissions in a consistent manner.

This chapter is presented *as published* as the peer-reviewed article *"Evolving Shipping Activity in Climate Scenarios: Coupling Econometrics with Integrated Assessment Model"* in *Ocean Engineering* (2025), DOI: 10.1016/j.oceaneng.2025.120516. The resulting shipping activity projections provide the essential input for the subsequent translation of trade flows into fleet requirements, energy demand, and fuel consumption.

3.1. INTRODUCTION

Our generation must address the ongoing challenge of climate change. This is mainly due to greenhouse gas emissions, especially CO_2. The Paris Agreement aims to limit global warming to well below 2°C, with a goal of keeping it under 1.5 °C [81]. Although the Agreement was unanimously accepted by the parties to the United Nations Framework Convention on Climate Change, it excludes major emitters from the international aviation and shipping sectors. According to Article 2.2 of the Kyoto Protocol, the International Maritime Organization (IMO) is tasked with regulating GHG emissions from international shipping [82].

The shipping sector is crucial in global trade, transporting over 80%

of goods by volume and more than 70% by value. 94% of the world's fleet primarily handles this extensive activity, contributing significantly to greenhouse gas emissions [83, 84]. Maritime shipping has accounted for CO_2 emissions of roughly 1.0 $GtCO_2$/yr in recent years (or 2.8% of global CO_2 emissions). Around 70% of this total originated from international shipping [4, 85]. As maritime shipping is inextricably linked to economic growth, sectoral emissions are expected to continue rising [39, 86].

Over the past decades, the IMO has introduced several measures to enhance energy efficiency and reduce carbon intensity in the shipping sector. Notable initiatives include the Energy Efficiency Design Index (EEDI) for new ships, the Energy Efficiency Existing Ship Index (EEXI) for existing vessels, and the Ship Energy Efficiency Management Plan (SEEMP) alongside the Carbon Intensity Indicator (CII) to improve operational efficiency [4, 87–90]. In 2023, the IMO revised its strategy, aiming for net-zero life-cycle GHG emissions around 2050 rather than 2100, including carbon dioxide removal (CDR) methods. This updated goal underscores the sector's commitment to global climate mitigation efforts [91]. However, the pathways to achieving this target are still unclear and uncertain.

To comprehend emission reduction targets, it is crucial to understand the entire process chain that leads to emissions. Emissions from maritime transport are closely tied to the composition of fuel supply, which depends on the demand for shipping activity. Also, recent fluctuations in the shipping market, such as COVID-19, have underscored the impact of this volatile demand [92]. An even greater source of volatility is the energy transition. Efforts to reduce the carbon intensity of transport will likely increase costs due to carbon taxes or the adoption of more expensive technologies and designs. This introduces significant uncertainty for the future market and investors in the sector. Therefore, understanding the evolving demand for shipping activity is essential.

In response to this uncertainty, models are required. So far, sectoral models have been used extensively to explore the decarbonization of international shipping [18]. However, these models often treat shipping demand as an exogenous variable, failing to capture significant connections to other aspects of the global economy. This limitation is critical because the shipping sector links product flows across regions and sectors, making it sensitive to regional developments and policy changes. Moreover, technological improvements and the transition to alternative marine fuels are closely linked to similar advancements in other energy-using sectors [93].

Integrated Assessment Models (IAMs) provide a valuable tool for addressing these limitations. IAMs have been extensively utilized to examine the consequences of different long-term climate mitigation strategies and have significantly impacted climate governance and policy. They offer a detailed representation of the world's energy, land use, agricultural, and climate systems, including interlinkages across sectors and regions over time. A common approach for exploring the future under complexity and uncertainty is developing a set of contrasting, plausible scenarios. These scenarios help understand how different factors interact, either working together or against each other, providing a systematic way to compare possible futures and guide climate policy-informed decisions [18, 42, 61, 94].

However, IAMs also have notable gaps. Long-term scenarios developed by these models often pay relatively little attention to emissions from international transport, typically projecting shipping demand through aggregated relationships with income and without differentiating cargo types. Recently, the IAM community has started to incorporate the specificities of international shipping, improving the representation of the sector's demand and mitigation options within these models. [42] used the TIAM UCL model [77] to project the future of energy product trade, translating energy trade flows into tangible metrics like tonnes and aiding in analyzing interregional energy commodity trade under various scenarios. The goal is to optimize energy trade to maximize global welfare and minimize energy system costs. [18] used the IMAGE model [95], where each region can import based on relative production and transportation costs, the latter depending on the distance. Fuel distribution from suppliers is determined using a multinomial logit equation, favoring the cheapest supplier. Also, [94] used the GCAM model [96] to improve the representation of shipping activity by modeling it explicitly in terms of service, such as ton-kilometers, for both international and domestic shipping. GCAM scenarios incorporate reduced shipping demand driven by carbon pricing and economic factors, factoring in price elasticity and the effects of carbon policies on activity levels.

Despite notable improvements in these recent studies, IAMs typically categorize countries as either pure exporters or importers, especially for energy cargoes. This results in neglecting the complexities of cross-trading, where a region can be both an importer and exporter of a specific product. This is important because fuel supply and emissions are related to the actual physical transport rather than the macroeconomic energy balance or trade value in monetary terms. Additionally, most current models primarily rely on cost optimization for estimating energy trade. This approach does not adequately account for non-cost factors such as bilateral political or geographical specifics, which can significantly influence trade patterns. A recent multi-IAM shipping study [61] has further emphasized this point, identifying the low representation of shipping activity as a key limitation across IAMs. Therefore, a coordinated effort to enhance shipping representations across multiple IAMs is required. In this paper, we aim to advance the representation of maritime shipping within IAMs, with a particular focus on the WITCH model. By leveraging the integrated framework, we incorporate macroeconomic drivers of shipping demand alongside detailed activity-based modeling. This enables us to produce more accurate projections and generate policy-relevant insights into the decarbonization of the maritime sector.

Building upon previous research, this paper introduces an econometric approach, an enhancement of the traditional gravity model of international trade, applied to various cargo types. Projections are made on bilateral trade flows calibrated on actual trade data, ensuring the capture of cross-trading effects. Subsequently, the econometric models are coupled with the WITCH IAM model [97]. For further policy analysis, this model is calibrated based on historical values and used to analyze the outcomes of multiple scenarios. Four distinct scenarios have been selected to assess the effects of mitigation efforts on seaborne shipping activity. They vary in their carbon tax scheme policies. The trade scenarios encompass nearly all seaborne traded commodities transported by dry bulk, wet bulk, and container vessels across 17 global regions.

This article is structured as follows: following this introduction, the methodology for econometric models, scenarios, and integration into the integrated assessment model is explained. Next, the results of the econometric analysis and the scenario runs are presented. Finally, we discuss the findings and their policy implications.

3.2. METHODOLOGY

Figure 3.1 depicts the methods outlined in this section used to develop shipping activity scenarios, consisting of two main components: econometric analysis and coupling with the Integrated Assessment Model. The econometric analysis involves three main approaches tailored to different non-overlapping cargo categories, aiming to identify and quantify the impact of influential macroeconomic factors on regional and bilateral trade for each cargo type. The specific cargoes analyzed include oil and petroleum products, LNG, coal, iron ore, grains, containerized cargo, and minor bulks. These eight cargoes are grouped into three main modeling categories: *energy cargo*, *non-energy major bulk*, and *minor bulk & containerized cargo*. The reference for choosing this categorization of cargoes is the Clarkson Shipping Intelligence Network (SIN) list of cargoes, excluding the not significant ones such as chemicals and vehicle trades. Our selected range of cargo covers more than 90% of global seaborne trade. We use historical data to identify patterns and determine elasticities within these models. Each model's specifics differ in terms of estimation method and influencing variables, which will be discussed in detail in the next sections. Subsequently, these econometric models and the derived elasticities are integrated into the WITCH IAM for policy evaluation and scenario development. The analysis is long-term and global in scope.

The aim is to obtain the elasticity of change of each chosen determinant variable on the amount of trade. The primary outcome of the model is the quantity of each traded cargo from one region to another on a mass basis. Then, by considering proxy ports for each region, the average distance between regions is obtained, and thus, the amount of seaborne transport work (mass × distance) is estimated. Calibration occurs for each cargo against the real data of the 2020 total seaborne trade. This study prioritizes reflecting maritime transport work by focusing on the seaborne portion of trade flows. While adjacent regions like Russia-China, Russia-Europe, Canada-USA, and the Rest of South America-Brazil heavily rely on pipelines and land transport for oil and petroleum products, these flows were not excluded. Instead, their seaborne components were extracted explicitly for analysis.

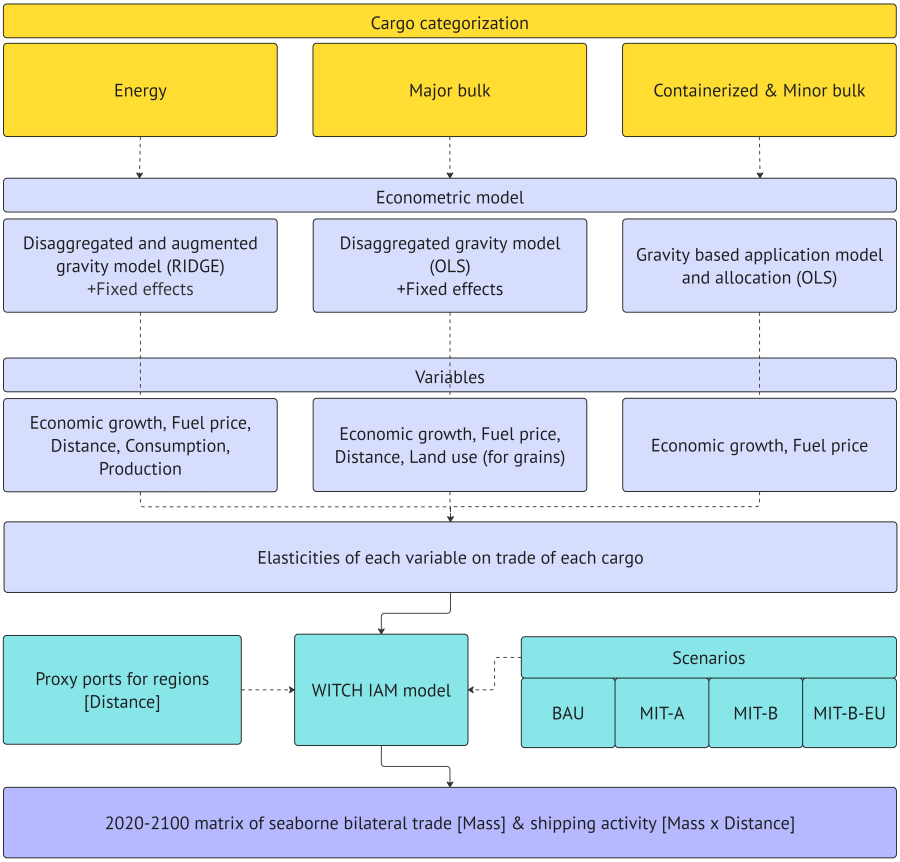


Figure 3.1.: Methodology framework.

3.2.1. ECONOMETRICS

While several theories explain international trade, such as comparative advantage [98] and the Heckscher-Ohlin model [99], the gravity model has emerged as the most commonly used framework [100, 101]. This model is based on the Armington assumption [102]. The basic gravity equation states that the trade flow between countries depends primarily on the size of the economies and the distance between importer and exporter. This model can effectively depict bilateral trade patterns [103, 104]. Authors in [105] concluded that cost-minimizing models provide relatively poor fits to observed behavior compared to a simple gravity model. The following expression shows the classical gravity model.

$$Trade(O, D) \propto \frac{GDP_{Origin}.GDP_{Destination}}{Distance} \tag{3.1}$$

Early applications of the gravity model in maritime contexts, such as analyzing seaborne coal and crude oil flows [105–107], primarily relied on including distance and national income as core predictors. Over time, these models evolved to accommodate more sophisticated features, such as country-specific fixed effects, energy structures, and political risks [100, 104], and to incorporate various trade-enhancing or inhibiting factors like colonial relationships and common language [108]. Furthermore, methodological extensions have emerged to improve predictive performance: gravity specifications have been combined with machine learning algorithms [108–110] and, more recently, graph auto-encoders [111] to capture complex relationships in bilateral trade. In maritime-oriented studies, these enriched models effectively evaluate shifts in LNG trading patterns and forest product exports [103, 104]. Also, studies such as [112–114] used various types of gravity models to forecast and analyze container shipping trade flows.

The gravity model is typically used to estimate the value of trade rather than its physical mass when aggregated over total trade [101]. However, in this paper, we will break it down for each cargo category to increase accuracy and use it to determine the mass of trade. This is important because the mass of trade affects transport work and leads to emission estimation, unlike trade value. Our approach to modeling trade flows recognizes that a single model cannot fit all types of cargo, yet we strive to keep the methodology as straightforward as possible. Estimating bilateral trade for each cargo category is a key objective that drives our approach. For energy cargoes, we augment the gravity model with variables such as production and consumption of the commodity, as well as fuel prices, alongside the traditional factors of GDP and distance. This allows for a more precise analysis of trade patterns in the energy sector. A similar model is employed for non-energy major bulk commodities like grains and iron ore. In the bulk model, production and consumption data from the IAM are not used because they are themselves derived from economic growth. To avoid double-counting GDP in both the production/-consumption projections and trade projections, we rely solely on GDP for the projections. Thus, the model for bulk commodities includes GDP, distance, and fuel prices as the primary variables, while for grain, land use for agriculture is also incorporated to capture the critical economic drivers. To ensure the accuracy of these models, a Variance Inflation Factor (VIF) test is conducted to assess multicollinearity among variables, allowing us to use the appropriate estimation method for accurate coefficient estimation. For minor bulk and containerized cargoes, a different methodology is necessary due to the diverse nature of these goods and the challenge of finding detailed bilateral and quantity-based data. Each subcategory within these groups, such as specific manufactured products in containerized cargo or distinct types of minor bulk goods, often represents a smaller share of total trade, making standard methods less applicable. Specifically, traditional methods fall short for manufactured goods typically shipped in containers due to the lack of reliable historical data by region in terms of weight. Instead, historical data is often available only in product values. A distinct approach was developed for containerized cargo to address these challenges, treating it as a separate commodity category. The method for minor bulk differs from that for all previous categories due to more limited data, necessitating a more aggregated approach. Both aim to estimate bilateral trade flows while considering each cargo type’s unique characteristics and data constraints. The analysis excludes other factors, such as environmental regulations, port infrastructure, common language, colonization, and political stability, as the focus is primarily on macroeconomic drivers and the impacts caused by climate policies.

ENERGY CARGO

The gravity model serves as a valuable tool for predicting bilateral trade. However, its applicability in energy cargo remains limited, with few exceptions, such as [104] and [115], who successfully utilized this model to estimate LNG trade flows. Additionally, [105] employed the Gravity and cost-minimizing models to compare the results for predicting coal seaborne trade using distance and transportation costs. Similarly, [106] applied the model to analyze crude oil exports using distance and supply & demand factors using AIS data. [107] adapted the model to specialize in international trade flows of coal, iron ore, and crude oil, incorporating GDP, distance, and a fixed component to account for trade habits and contracts.

In this study, we will modify the gravity model and make it specialized for determining the bilateral trade of fossil fuel energy commodities: crude oil & petroleum products, natural gas, and coal. This is done by predicting variables and using a fixed-effect component. Adding more cargo-specific determinants increases the reliability of results. Fixed-effect controls the unobserved heterogeneity in data such as bilateral trade momentum and agreements [103, 116]. To improve the estimation method and find the elasticities of change of each determinant, a log-log linearization is done to the equation [117, 118]. The equation comes as follows:

$$\ln Trade_{OD,t} = \beta_0 + \beta_1 \ln V_1 + \beta_2 \ln V_2 + \cdots + \beta_n \ln V_n + \eta_{OD} \tag{3.2}$$

Where $Trade_{OD,t}$ is bilateral trade flow, β_n is the elasticity of the determinant variable of V_n, and η_{OD} is the origin-destination fixed-effect components. The variables to include in the study are the GDP, production, and consumption of both importer and exporter regions and the average distance of shipping and fuel prices. The rationale behind choosing GDP is straightforward as it is a primary determinant of trade and a proxy of economic growth [39, 45, 113, 119]. Distance and fuel price are proxies for transport costs [100, 120]. An escalation in the price of bunker fuel is expected to reduce trade volume, particularly for imports from distant regions. The interplay between production, consumption, and regional supply-demand dynamics significantly impacts global trade. For exporting countries, the availability of natural resources and their extraction/production directly influences their capacity and willingness to export. Higher reserves indicate a secure energy future, encouraging exports to increase revenue. Therefore, production levels are a key factor, representing the country’s ability to supply the market. On the import side, When a country’s domestic production falls short of its consumption needs, it must rely on imports to meet demand and ensure economic stability [100, 104, 115]. Consumption and production of oil are crucial variables for both crude oil and petroleum products.

The empirical data used in this study was based on open-source data banks. BPstats [121] was used as the main source of data for bilateral energy trade flow for 2014-2021. The data for sea trade was extracted, and marginal flows -less than 0.005 million tonnes- were excluded. The same reference is used also for regional production and consumption of energy sources. The World Bank was used to gather the GDP values of the regions [122]. All values are normalized based on 2005 USD to dampen the effect of inflation. The global average bunker price value is gathered from Clarkson Research Services [123]. After collecting all the data, they were organized to create a panel dataset containing every bilateral trade flow of each commodity. Zero flows have been removed from the dataset as suggested by [116] and [124].

A variance inflation factor (VIF) test was performed to assess the presence of multicollinearity among the variables in the dataset. Substantial multicollinearity, indicated by a high VIF, suggests a variable is highly correlated with others, potentially leading to inflated standard errors and unreliable coefficient estimates in the regression model [125]. In this case, the RIDGE estimation method is recommended over ordinary least squares (OLS)[126]. RIDGE introduces a penalty to the magnitude of coefficients, thereby reducing their variance and enhancing stability in the presence of correlated predictors. The presence of multicollinearity, as evidenced by VIF values higher than 5, calls for adopting the RIDGE method. The table of VIF values is presented in the appendix. The dataset is split into two parts: 80% for training and 20% for testing. To increase the reliability of the results, k-fold cross-validation is implemented.

MAJOR BULK CARGO

The primary cargoes examined in this section are whole cereals, including wheat, rye, barley, oats, maize (corn), rice, grain sorghum, and iron ore (and concentrates, including roasted iron pyrites) [1]. Historical bilateral trade data obtained from Trade Map [127] (2015-2021) are used in econometric models to measure trade elasticities for each commodity. The analysis uses bilateral data, including the GDP of both exporting and importing regions, distance, fuel prices, and, for grains specifically, the area of exporters' agricultural land use [2], to estimate trade flows by region and commodity, using 2020 as the baseline year. A fixed-effects component is included to account for bilateral trade momentum.

Similar to the energy cargo approach, the dataset is split into a training set (80%) and a test set (20%), with k-fold cross-validation used to improve the reliability of the results. The general approach remains consistent, as the production and consumption of these commodities are also generally influenced by GDP. Including GDP as a determinant variable in the models prevents redundancy while addressing the key factors driving trade flows. The primary differences lie in the specific variables selected and the estimation methods used, guided by the results of the VIF test. The OLS estimation method is used here because multicollinearity does not exist in these datasets.

MINOR BULK & CONTAINERIZED CARGO

This study utilizes econometric models to estimate bilateral trade flows of containerized cargo, using data from Clarkson's SIN database [129] covering regional exports and imports from 2002 to 2021, supplemented with regional GDP figures and global average fuel prices for each year. We employed OLS regression to quantify the coefficients of trade flows to GDP and fuel prices, represented by coefficients (betas). The core equation includes a general trade model, which predicts trade volumes using GDP and fuel prices, and another function that distributes the trade among regions to form bilateral trade. Specifically, the general trade

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[1] The HS code for iron ore is 2601, and for grains, it ranges from 1001 to 1008

[2] [128]

equation models the relationship among trade (imports or exports), GDP, and fuel prices, whereas the bilateral trade equation estimates the trade volume between an origin and destination region over time, accounting for the proportional allocation of trade.

$$Trade_{X/I}(t, O/D) = \beta 0_{I/X} \times GDP^{\beta 1_{X/I}} \times fprice^{\beta 2_{X/I}} \tag{3.3}$$

$$\begin{aligned} Trade_{OD,t} = Import_D(t_0) \times \exp\left(\beta 1_I \cdot \ln\left(\frac{GDP_D(t)}{GDP_D(t_0)}\right)\right. \\ \left. + \beta 2_I \cdot \ln\left(\frac{fprice(t)}{fprice(t_0)}\right)\right) \\ \times \frac{Allocation_O(t)}{\sum_O Allocation_O(t)} \end{aligned} \tag{3.4}$$

$$Allocation_O(t) = \beta 0_X \times GDP^{\beta 1_X}(t) \times fprice^{\beta 2_X}(t) \tag{3.5}$$

The trade equation for modeling containerized cargo flows consists of three main multiplicative components. The first component, $Import_D(t_0)$, represents the base-year import volume at the destination. The second component predicts import growth by considering changes in GDP and fuel prices from the base year t_0 to the current year t. The coefficient β_1 represents the elasticity of trade flow to GDP, and β_2 represents the elasticity to fuel price. The third component, $\frac{Allocation_O(t)}{\sum_O Allocation_O(t)}$, allocates the predicted import volume to various exporting regions based on economic factors at the origin. In this term, $Allocation_O(t)$ is a function of the origin's GDP and fuel price, capturing the proportion of total imports attributed to each origin. Together, these components provide the model for estimating containerized cargo trade flows, incorporating base-year data, growth predictions, and import allocation among exporting regions.

Regarding the minor bulk, time-series data of total global trade are available[129]. A similar equation to containerized cargo applies to this category as well. Afterward, bilateral trade is allocated according to each region's economic growth at each time step. The approach is similar to containerized cargo, with the difference that regional coefficients are non-differentiated due to data limitations.

MODELS' VALIDATION

The econometric models were validated using recently released data from 2022 and 2023. Initially trained on data up to 2021, the models were tested against this holdout set to assess their predictive performance. This approach ensures the models can generalize to new observations, reflecting their applicability in dynamic trade environments.

Validation metrics, including R-squared (R^2), mean squared error (MSE), root mean squared error (RMSE), and mean absolute error (MAE), were computed to evaluate the models' predictive accuracy. Additionally, actual versus predicted trade values were plotted for visual inspection. The validation results demonstrate strong performance across all model categories, with high R^2 values and minimal errors observed in key metrics. The models successfully captured trade dynamics across diverse cargo types. For further validation, this study compares results with similar studies that predict global shipping demand. Validation plots and a metrics table are provided in B.1.

3.2.2. COUPLING WITH THE INTEGRATED FRAMEWORK

After creating models for each cargo type and estimating each predictive variable's impact on bilateral trade, the models are integrated into an Integrated Assessment Model to develop scenarios and evaluate policies. The following sections provide a detailed explanation of the IAM framework and the scenarios.

INTEGRATED ASSESSMENT MODEL (IAM)

IAMs describe key processes in the interaction of human development and the natural environment. Typically, they are designed to assess the implications of achieving climate objectives, such as limiting global warming to 2° or 1.5° [61, 130, 131]. These models are crucial for exploring future climate actions and informing policy decisions [132]. IMO relies on these models for future projections of the sector.

This study employs the WITCH IAM, a renowned model featured in the IPCC Assessment Reports [1, 133]. The model integrates a hybrid structure that combines top-down macroeconomic intertemporal optimization with bottom-up technological insights into the energy sector. It emphasizes optimal mitigation and adaptation strategies for climate change, accounting for regional welfare, free-riding behaviors, and externalities. A social planner approach maximizes regional utility, considering fossil fuel and GHG mitigation costs. A key strength lies in its detailed representation of energy and economic sectors. However, the international shipping module was in its early stages and highly aggregated [61]. The model operates with a time horizon extending to 2100 and utilizes intertemporal optimization with perfect foresight. It adopts a general equilibrium solution concept and applies a flexible discount rate based on the Ramsey rate, typically ranging from 3.0 to 5.0 percent per year. The current version, WITCH 5.0, encompasses 17 regions defined by geographic, income, and energy demand characteristics. Fossil fuel extraction is handled by requiring a capital investment for production, which depreciates over time. Costs increase with resource depletion, with different oil grades having varying costs and emissions. The model uses fossil fuel availability curves for coal and gas extraction, aligning production with international prices and market demand. Further technical details are available in the WITCH 5.0 Documentation [134, 135].

PORTS AND DISTANCES

To approximate the distances involved in international trade, we identified the largest ports in each region as proxy ports; for Sub-Saharan Africa, the USA, and Canada, both east and west-coast ports were used to capture diverse shipping routes. Sea distances between these ports were obtained from an online tool [136], which provides multiple route options, ranging from shortest to longest. The routes pass through chokepoints such as the Panama Canal and Suez Canal, subject to ship-size limits, and through passages such as Cape Horn and the Cape of Good Hope, which impose no vessel-size constraints. The permissible vessel sizes for each route were extracted and matched with the proportions of different vessel types, as reported in the IMO's 4th GHG study, along with corresponding cargo categories. A weighted average distance was then calculated using the shortest feasible route for each ship-size class and cargo type, ensuring that the respective size limitations and vessel shares were accounted for. Additional data used to construct the spatial distance matrix, and sources are provided in Appendix C. An illustrative example is the route between Europe's Port of Rotterdam and Japan's Port of Chiba; where the shortest distance (11,195 nautical miles) is via the Suez Canal, but oil tankers larger than Suezmax (i.e., ULCC or VLCC) must travel via the Cape of Good Hope, which extends the route to 14,511 nautical miles. Since 61% of tanker capacities can still pass through the Suez Canal, the weighted average distance is calculated as:

$$Avg.Distance : [0.61 \times 11195 + 0.39 \times 14511] = 12488 \text{ nautical miles}$$

Although this approach involves rough assumptions, it provides a sufficiently accurate estimate, as the primary need is for an average distance. A calibration process will subsequently align these estimates with actual 2020 shipping data. Figure 3.2 shows the regions and proxy ports for each region. Route and port traffic congestion is neglected in this study.

SCENARIO SELECTION

The shared socioeconomic pathways (SSPs) are scenarios designed to depict global socioeconomic developments throughout the 21st century. The climate change research community created these scenarios to provide a unified framework for analyzing long-term climate impacts, vulnerabilities, and strategies for adaptation and mitigation [40, 137, 138]. SSP2, or middle-of-the-road, is used as the baseline of scenarios. In the SSP2 narrative, a sort of midpoint between the other SSPs, socioeconomic indicators progress compatibly with historical trends, and there

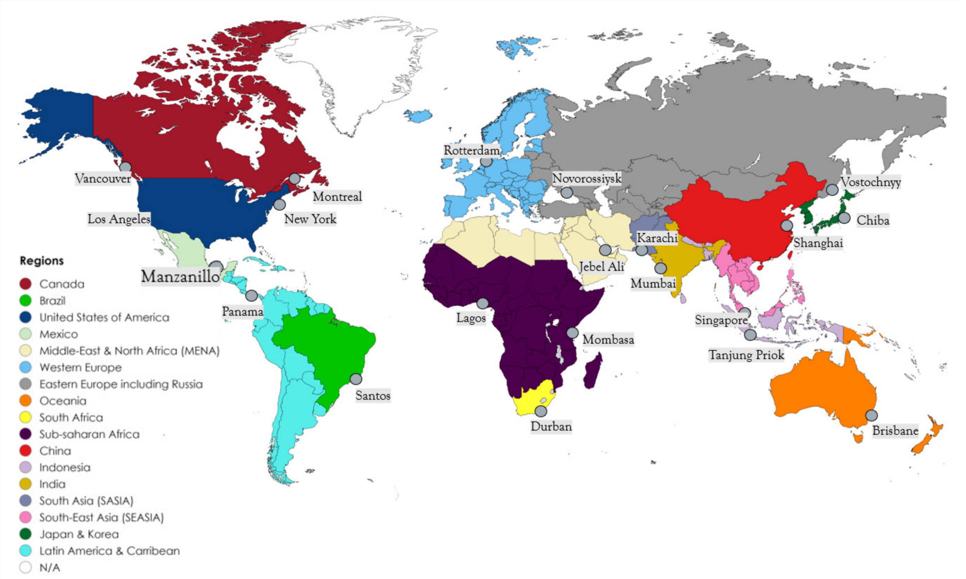

Figure 3.2.: Representative regions and proxy ports.

are no major technological disruptions [139]. The key distinction between the scenarios lies in the portfolio of the global carbon tax. In the non-MIT scenario, no carbon tax is implemented. Thus, the global trend is to continue using fossil fuels and to invest less in renewable energy. In this scenario, the average global surface temperature increases by 3.5° by the end of the 21st century. In scenario MIT-A, a uniform carbon tax is implemented to align with a 2° global temperature increase. Meanwhile, scenario MIT-B portrays a more rigorous carbon policy to limit the temperature increase to 1.5°. The MIT-B-EU scenario mirrors MIT-B, with the notable difference being that Europe adopted carbon tax two decades earlier than other regions. The details of the scenarios are presented in a table 3.4 and figure 3.17 in the 3.6.

3.3. ECONOMETRICS RESULTS

3.3.1. ENERGY CARGO

The table 3.1 presents elasticity estimates and model performance for coal, LNG, and oil products, focusing on the drivers of seaborne trade. Production is the most influential factor for coal trade in the exporting country, with a positive elasticity of (0.619), while distance has a significant negative impact (-0.287). LNG shows similar dynamics, with a robust positive elasticity for production in the exporter country (0.807) and a significant negative effect from distance (-0.589). In oil products, the key drivers are production in the exporter country (0.426) and consumption in the importer country (0.453). Only for oil and oil products is the elasticity of exporter consumption positive, as the transformation of crude oil into petroleum products is recorded as crude oil consumption in the data, even though it reflects petroleum product production. Price negatively impacts all cargoes, and GDP elasticities vary depending on whether they apply to exporters or importers. The model performs well, with R² scores ranging from 0.802 for coal to 0.949 for oil products, indicating robust predictive accuracy. These results emphasize that production and distance are the main determinants of energy trade, with varying degrees of sensitivity across different cargoes.

Table 3.1.: Elasticity Estimates and Model Performance for Energy Cargoes.

	Coal	**Coal Std. Dev**	**LNG**	**LNG Std. Dev**	**Oil Products**	**Oil Products Std. Dev**
Elasticities						
Production Exporter	0.619	(0.075)	0.807	(0.045)	0.426	(0.024)
Consumption Importer	0.300	(0.015)	0.429	(0.020)	0.453	(0.030)
Production Importer	-0.092	(0.012)	-0.301	(0.016)	-0.006	(0.010)
Consumption Exporter	-0.335	(0.084)	-0.541	(0.038)	0.154	(0.022)
Fprice	-0.322	(0.083)	-0.030	(0.009)	-0.036	(0.008)
Distance	-0.287	(0.019)	-0.589	(0.015)	-0.709	(0.013)
GDP Importer	0.219	(0.047)	0.375	(0.022)	0.258	(0.037)
GDP Exporter	-0.329	(0.039)	-0.063	(0.029)	-0.174	(0.046)
Metrics						
Average R2 Score	0.802	(0.088)	0.819	(0.088)	0.949	(0.012)
Average RMSE	0.500	(0.113)	0.428	(0.113)	0.322	(0.033)
Average MSE	0.263	(0.128)	0.184	(0.128)	0.105	(0.021)
Average MAE	0.402	(0.077)	0.308	(0.077)	0.256	(0.025)

3.3.2. MAJOR BULK CARGO

The table 3.2 presents the effects of various factors on the grain and iron trade. Grain imports are highly sensitive to the GDP of importing countries (elasticity 0.259), while distance negatively affects trade (-0.197), and the exporter's GDP has less impact. In iron trade, the exporter's GDP is the dominant factor (0.474), while the importer's GDP and distance play a more minor role. The models perform well, with high R² scores of 0.902 for grain and 0.941 for iron and low error metrics, indicating predictive solid accuracy.

Table 3.2.: Elasticity Estimates and Model Performance for Grain and Iron.

	Grain	Grain Std. Dev	Iron	Iron Std. Dev
Elasticities				
GDP Exporter	0.148	(0.006)	0.474	(0.050)
GDP Importer	0.259	(0.008)	0.177	(0.114)
Distance	-0.197	(0.012)	-0.168	(0.019)
Fprice	-0.089	(0.018)	-0.103	(0.013)
Agricultural land-use Exporter	0.149	(0.007)	-	-
Metrics				
Average R2 Score	0.902	(0.008)	0.941	(0.007)
Average RMSE	0.257	(0.026)	0.272	(0.026)
Average MSE	0.067	(0.013)	0.075	(0.014)
Average MAE	0.151	(0.013)	0.145	(0.012)

3.3.3. MINOR BULK & CONTAINERISED CARGO

The table 3.3 displays coefficients ($\beta_0, \beta_1, \beta_2$) for the import and export of each region. It also shows the model performance metrics for containerized cargo trade across different regions. The elasticity values indicate how sensitive trade volumes are to changes in price and GDP. Economic growth in all importing and exporting regions substantially impacts trade volumes, with the highest impact observed in Europe and MENA. On the other hand, the price elasticity for most imports and exports is negative, indicating that higher prices reduce import volumes. The R^2 values range from 0.822 to 0.991, showing the models' strong ability to explain variations in trade volume. The performance metrics further confirm the models' good fit and accuracy.

Table 3.3.: Elasticity Estimates and Model Performance for Containerized Cargo by Region and Trade Direction.

Region	Trade Direction	Constant	Price Elasticity	GDP Elasticity	R^2	MSE	MAE
Oceania	Import	2.201	-0.327	0.882	**0.956**	0.003	0.050
	Export	1.323	-0.211	0.597	**0.956**	0.002	0.033
North America	Import	0.894	-0.064	0.865	**0.864**	0.005	0.056
	Export	0.340	0.168	0.554	**0.886**	0.003	0.042
MENA[3]	Import	1.817	-0.350	1.233	**0.991**	0.001	0.034
	Export	1.194	-0.429	1.210	**0.950**	0.007	0.071
LACA[4]	Import	1.197	-0.252	0.910	**0.902**	0.007	0.061
	Export	1.529	-0.250	0.613	**0.663**	0.011	0.091
Indian sub-continent	Import	1.313	-0.056	0.831	**0.986**	0.003	0.038
	Export	0.966	-0.008	0.692	**0.986**	0.002	0.031
Far-East	Import	1.802	-0.063	0.865	**0.979**	0.003	0.042
	Export	2.159	-0.039	0.822	**0.962**	0.004	0.053
Europe	Import	0.017	-0.196	1.595	**0.892**	0.006	0.066
	Export	1.737	-0.135	1.678	**0.760**	0.014	0.102
Africa	Import	2.484	-0.379	1.327	**0.947**	0.009	0.082
	Export	0.966	-0.036	0.391	**0.910**	0.002	0.034

Regarding the minor bulk, log-log multiple regression results revealed that a 1% increase in GDP is associated with a 0.83% rise in trade, while a 1% increase in fuel price results in a 0.15% decrease in trade. The model has high explanatory power ($R^2 = 0.97$) and accurately predicts trade values with low errors (MAE = 0.03, RMSE = 0.043). Due to a lack of detailed data, the estimated elasticities are global and aggregated over all regions for this category. Additional information and validation of all econometric models are presented in tables B.1 to B.5 and figs. B.1 and B.2 in the appendix.

3.4. SCENARIO RESULTS AND DISCUSSION

3.4.1. FUTURE OF INTERNATIONAL SHIPPING DEMAND

Global seaborne trade is projected to grow throughout the century, with the extent of growth heavily influenced by carbon policies. Shipping activity demands are expected to grow by 34-66% by mid-century, with 2020 as the base year. In the non-MIT scenario, which lacks carbon regulations, trade could exceed 150 trillion ton-miles per year by 2100. In contrast, the MIT-A scenario, aligned with limiting global temperature rise to 2 degrees Celsius, shows moderated growth, reaching around 125 trillion ton-miles. The MIT-B scenario, targeting a 1.5-degree limit, leads to even slower growth, just over 100 trillion ton-miles, driven by strict carbon regulations that reduce fossil fuels trade while boosting cleaner energy sources. In the MIT-B-EU scenario, where Europe enforces carbon taxes earlier, trade growth initially surpasses even the non-MIT scenario due to shifts in trade flows, which is explained later. However, it converged with the MIT-B results after the mid-century, reaching slightly below 100 trillion ton-miles.

Figure 3.3 shows the amount of projected aggregated seaborne trade in mass and transport work in four scenarios. Figure 3.4 shows the same but indexed and disaggregated by different cargo.

3.4.2. TRADE IN ENERGY CARGO

The non-MIT scenario projects the highest trade of fossil fuel energy commodities due to the absence of carbon policies. In this scenario, traditional exporters, such as the Middle East and the USA, maintain their dominance throughout the century, with stable trade patterns reflecting continued reliance on fossil fuels.

Interestingly, in the early years of the MIT-B-EU scenario, where only Europe enforces a carbon tax, there is initially higher trade in oil products compared to the non-MIT scenario. This paradox arises because Europe's carbon tax reduces domestic oil consumption, causing an excess supply that lowers global oil prices. Lower prices make oil more affordable for countries without carbon taxes, boosting their consumption. Additionally, reduced European demand shifts the investments to non-taxed regions, enhancing their oil production. As a result, global oil consumption

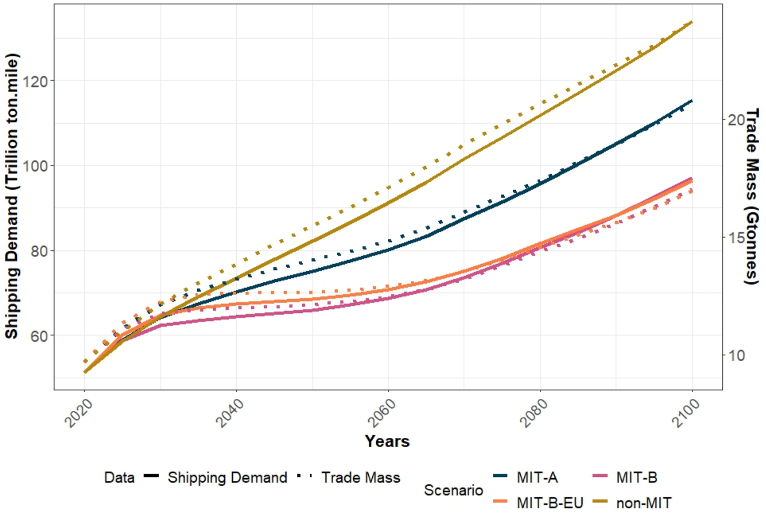

Figure 3.3.: Aggregated global sea trade of four scenarios.

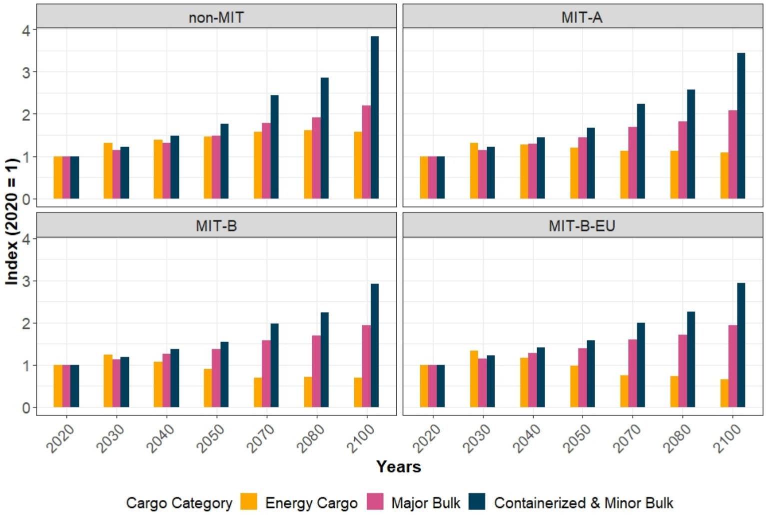

Figure 3.4.: Global sea trade growth of four scenarios by cargo categories.

and extraction initially rose despite Europe's reduced usage, driven by increased demand and production in regions without carbon taxes. However, as other regions implement carbon taxes, global trade patterns shift towards convergence with the MIT-B scenario, characterized by reduced fossil fuel trade and increased diversification of energy sources.

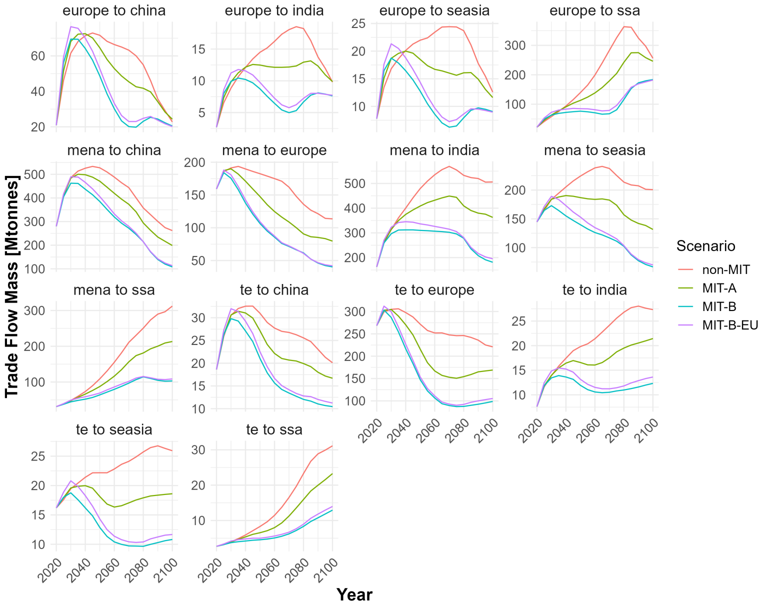

Figure 3.5.: Major sea routes of oil & products trade shifts over time and scenarios.

As shown in figure 3.5, there is a marked divergence in trade route trends for oil products depending on the scenario. Major routes such as MENA (Middle East and North Africa) to India and Seasia show a steady increase in trade volumes under the non-MIT scenario before it reaches a plateau, suggesting sustained demand for oil in these regions. In contrast, trade volumes along these routes decline sharply under the MIT-B and MIT-B-EU scenarios. China imports are peaking around 2045 and then declining, while in the MIT scenarios, the peak happens even sooner. These indicate that stricter climate policies could significantly reduce oil demand, particularly in Asia, where energy policies may shift away from fossil fuels. The most influenced routes through these scenarios are MENA-India, TE-Europe, and MENA-Seasia. Additionally, the MENA to SSA (Sub-Saharan Africa) route shows an upward trend across all scenarios, with a spike in the non-MIT scenario, highlighting SSA's growing role as a significant oil importer due to increased industrial activity and energy consumption.

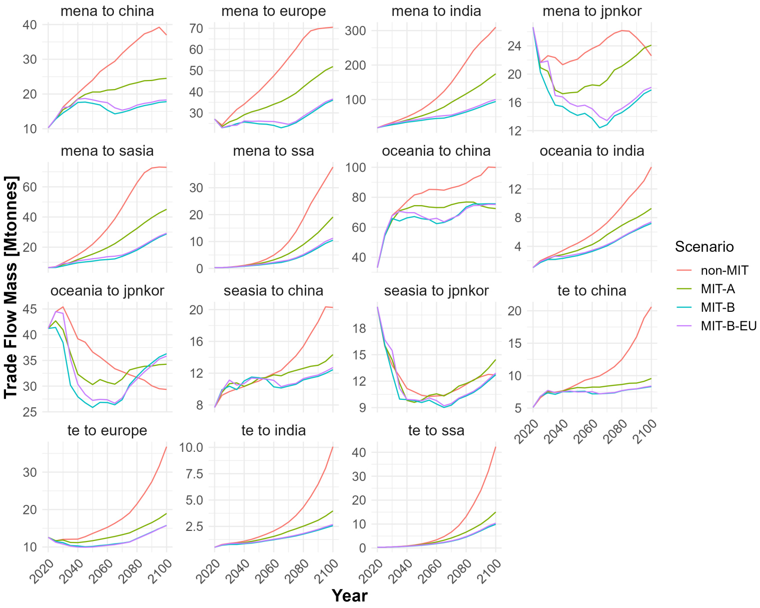

Figure 3.6.: Major sea routes of LNG trade shifts over time and scenarios.

In figure 3.6, LNG trade routes reveal stable or shifting patterns depending on the region and scenario. Routes such as MENA to India and MENA to Europe display significant growth in trade volumes under the non-MIT scenario, indicating higher future demand for natural gas as a transitional energy source. However, under the MIT-B and MIT-B-EU scenarios, trade volumes along these routes will stabilize or decline slightly by 2050, suggesting a shift towards renewable energy sources and reduced reliance on natural gas. This trend is particularly evident in the MENA to Europe route, where trade volumes decrease under stricter scenarios, indicating potential changes in Europe's energy import strategies and consumption patterns. Some routes, such as MENA to Jpnkor, trend upward or downward depending on the scenario, reflecting the variability caused by carbon policies. The most influenced routes through these scenarios are MENA-Europe and MENA-China.

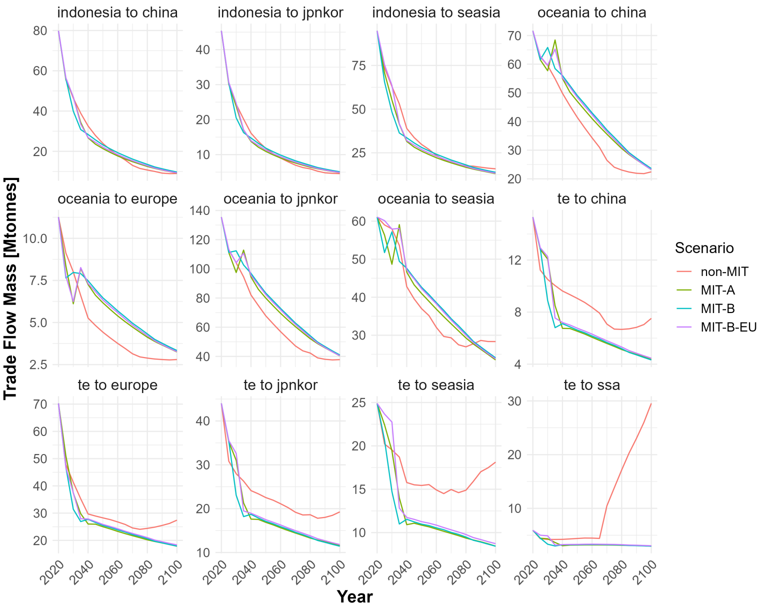

Figure 3.7.: Major sea routes of coal trade shifts over time and scenarios.

Coal trade flows show a clear and consistent decline across all scenarios, with the steepest drops occurring under the MIT-B and MIT-B-EU scenarios. The competitiveness of alternative sources primarily drives the decline in coal consumption and production for energy generation. Renewable energy has become cost-competitive, decreasing coal demand, particularly in advanced economies. It is expected that global coal demand will continue to fall. Additionally, The aging coal infrastructure further increases the cost of coal, making investments in renewables or natural gas more attractive. These factors contribute to a sustained decrease in coal usage even under current measures without requiring stricter climate policies [140]. Also, in all scenarios of the IPCC 6th report, [141] compiled all coal projections and concluded that the global coal supply will rapidly decline, with coal use without CCS largely phased out entirely by 2040.

According to figure 3.7, key routes, such as Indonesia to China and Indonesia to Japan and Korea, exhibit a sharp reduction in trade quantity, reflecting a global move away from coal in favor of cleaner energy sources. Exports from Oceania are also significantly affected, similar to Indonesia, as demand for coal diminishes. In the non-MIT scenario, trade of routes involving Oceania exports is lower compared to the MIT scenarios. This is because the importer's reduced coal consumption has a more significant impact on the MIT scenarios. The most influenced routes through these scenarios are TE-Seasia and TE-Jpnkor. An interesting point is the upward trend of exports from TE to SSA after 2060 in the non-MIT scenario, driven by high consumption and growth in SSA. This is not happening in MIT scenarios, as the region’s demand is satisfied by cleaner energy sources.

3.4.3. TRADE IN MAJOR BULK CARGO

Iron ore and grains trade is projected to increase steadily as population growth and economic expansion drive higher demand. However, in mitigated scenarios with stricter carbon policies, the growth rate is slightly lower due to higher average fuel prices and higher abatement costs, which raise transportation costs and represent the economic cost of climate mitigation. The results show that grains and iron ore trade are less sensitive to climate policies and more driven by the combined effects of population and economic development. By 2100, shipping demand for grains is expected to remain between 9 and 11 trillion ton-miles, while iron ore demand is projected to stay between 20 and 24 trillion ton-miles. The divergence of scenarios usually starts to build up after around 2040.

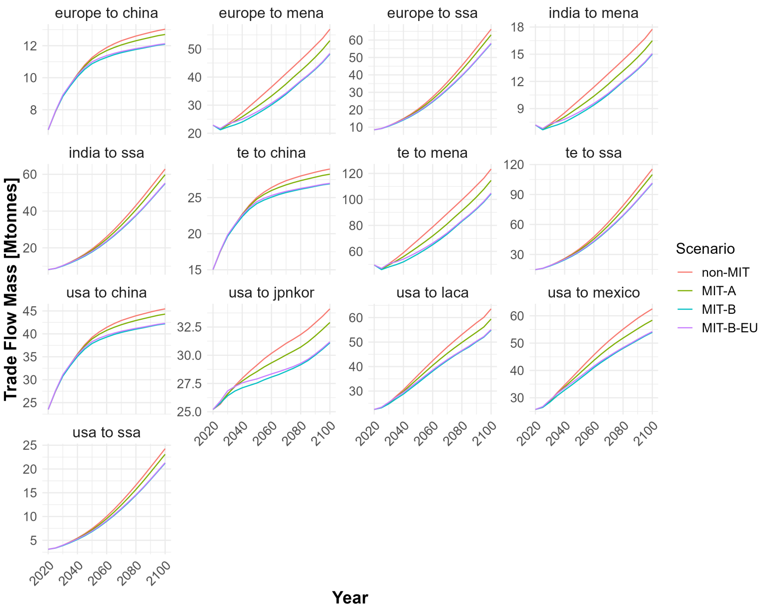

Figure 3.8.: Major sea routes of whole grains trade shifts over time and scenarios.

Grain main trade routes in figure 3.8 show significant increases in trade volumes, particularly to Sub-Saharan Africa and MENA. For example, the Europe to SSA route demonstrates continuous growth under all scenarios, with the highest increases observed in the non-MIT scenario. This trend reflects rising food import needs driven by population growth and economic development. Similarly, grain trade volumes to MENA increase steadily, highlighting the region's dependency on grain imports to meet food security requirements. Notably, some routes, such as USA to JPNKOR under the MIT-B-EU scenario, show higher trade volumes, even slightly surpassing the non-MIT scenario, due to the lower global fuel prices explained earlier. The relatively uniform growth across scenarios suggests that grain trade is influenced mainly by demographic and economic factors rather than climate policy alone. The most influenced routes through these scenarios are TE-MENA and TE-SSA.

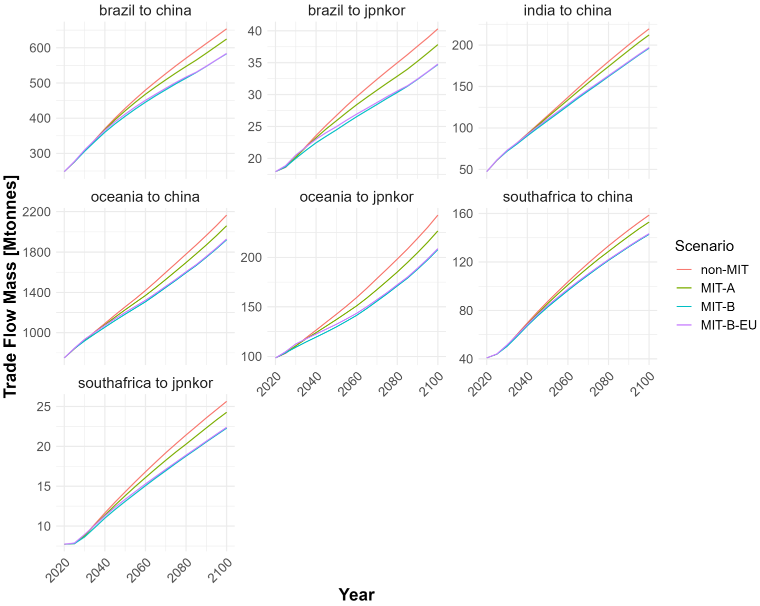

Figure 3.9.: Major sea routes of iron ore trade shifts over time and scenarios.

As shown in Figure 3.9, the Iron ore trade remains robust across all scenarios, particularly on major routes such as Oceania to China. Trade volumes on this route increase steadily, even under the MIT-B and MIT-B-EU scenarios, although the growth rate is lower than in the non-MIT scenario. This suggests that the demand for iron ore, driven by infrastructure development and construction in regions such as China, remains strong despite potential shifts toward sustainability and environmental regulation. The most influenced routes are Oceania-China and Brazil-China, reflecting their significant roles in meeting China's iron ore demand.

3.4.4. TRADE IN CONTAINERIZED CARGO AND MINOR BULK

Minor bulk and containerized cargo are projected to increase steadily and faster than other types of cargo due to their strong dependence on economic growth and population expansion. By 2100, the demand for containerized cargo is expected to range between 35 and 45 trillion ton-miles, while the demand for minor bulk is projected to be between 23 and 30 trillion ton-miles. This reflects their heightened sensitivity to economic activity and the overall expansion of the global economy.

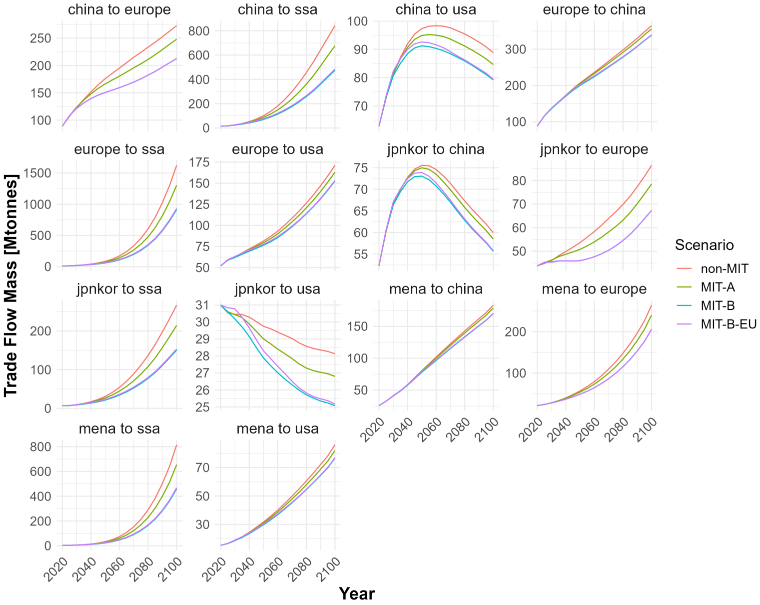

Figure 3.10.: Major sea routes of containerized trade shifts over time and scenarios.

In figure 3.10, trade routes for containerized goods consistently show strong growth across all scenarios, particularly routes to Sub-Saharan Africa. For instance, the Europe to SSA route experiences a continuous rise in trade volumes, reflecting SSA's expanding economic integration and increasing demand for consumer goods and manufactured products. Despite stringent climate policies like MIT-B and MIT-B-EU, these routes demonstrate upward trends, although the growth rate is slightly lower than in the non-MIT scenario. Interestingly, routes such as China-USA and Jpnkor-China peak around 2050-2060 and then decline, with the peak occurring sooner under the MIT scenarios. The Jpnkor-USA route is the only route showing a general decline across all scenarios. The most influenced routes through these scenarios are those where SSA is an importer as well as the China-Europe route. The robust growth in containerized goods trade to SSA and other emerging markets suggests a shift in global trade hubs and a move towards more diversified trade networks driven by economic growth and infrastructure development in these regions.

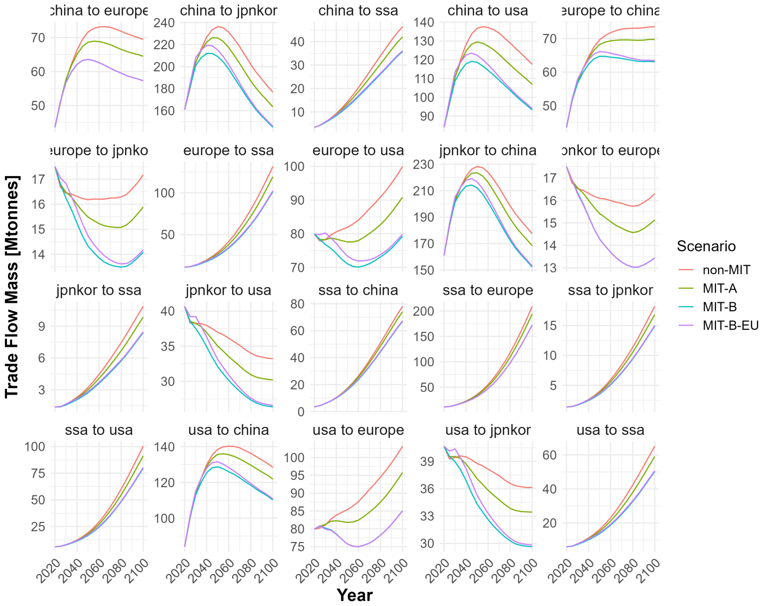

Figure 3.11.: Major sea routes of minor bulk trade shifts over time and scenarios.

Illustrated by figure 3.11, Trade flows for minor bulks, which include a variety of bulk goods, depending on the scenarios. Regarding the shifting patterns, the China-Jpnkor route peaks around 2050 and then declines, with the peak occurring sooner under the MIT scenarios. A similar pattern is observed for the China-USA and Jpnkor-China routes. Some routes, such as SSA-Europe and SSA-USA, show sharp increases that are almost inelastic to the scenarios. Other routes' behavior entirely depends on the scenario, such as Europe-USA and USA-Europe, which decline in the MIT-B and MIT-B-EU scenarios but increase in the non-MIT and MIT-A scenarios. The most influenced routes are China-Jpnkor, both ways around, reflecting their significant role in minor bulk trade flows. The overall trends remain consistently upward across scenarios.

3.4.5. DISCUSSION

- **Stricter carbon policies and higher carbon taxes are projected to reduce global seaborne trade** mainly due to mitigation-related economic loss and shifting fossil fuel production and consumption patterns. This decrease in trade is particularly significant for fossil fuel cargoes. These trends highlight the importance of cautious investment strategies for port infrastructure. Specifically, facilities heavily reliant on fossil fuel cargoes should plan for reduced volumes while opportunities may arise to adapt infrastructure for cleaner energy products and resilient trade flows in non-energy sectors.

- **The total trade share of different cargoes is expected to shift**, with oil products, containerized cargo, minor bulk, and iron ore dominating by end-century across all scenarios. The trade of minor bulk goods and iron ore remains less sensitive to climate policies and is driven more by economic activity and manufacturing needs. Stakeholders should monitor these trends and invest in adaptable logistics and handling facilities to accommodate traditional and emerging cargoes. Shipowners might consider diversifying their fleets to include vessels capable of transporting various cargo types [Figure 3.12]. There is potential for new trade markets, such as biomass and hydrogen, to emerge, although these are not explicitly covered in this study.

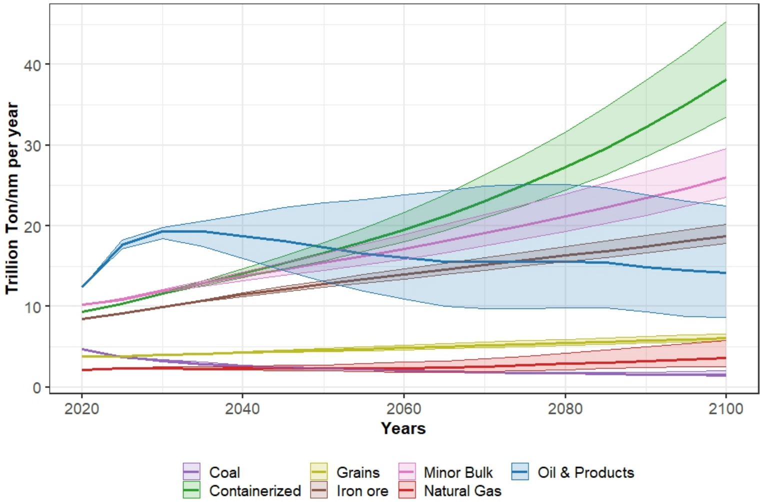

Figure 3.12.: The range of projected shipping demand of cargoes across scenarios.

- **If Europe implements a carbon tax before other regions, it is expected to increase the seaborne trade, especially oil products.** This is because Europe will likely reduce its consumption of oil products, resulting in an excess oil supply in the global market and subsequently causing a reduction in global oil prices. Low-cost producers like those in the Middle East maintain or even expand production. Additionally, the increase in the export of fossil fuels from Europe to the non-taxed regions will stimulate seaborne trade. The trade of other cargoes also increases slightly due to lower global fuel prices. This will change when other regions implement carbon taxation starting in 2035 [Figure 3.13]. Policymakers should aim to coordinate global efforts in implementing carbon taxes to avoid unintended regional trade imbalances and ensure fair competition. A harmonized approach to carbon taxation would prevent market distortions and unintended emission increases. As the first to implement a carbon tax in shipping, Europe should invest taxation revenues in dual-use port infrastructure and vessels adaptable to alternative energy cargoes while subsidizing cleaner shipping technologies such as carbon-neutral fuels and energy-efficient vessels. This strategy would future-proof trade routes, accelerate the global energy transition, and position Europe as a leader in decarbonizing maritime trade, balancing short-term economic gains with long-term climate goals.

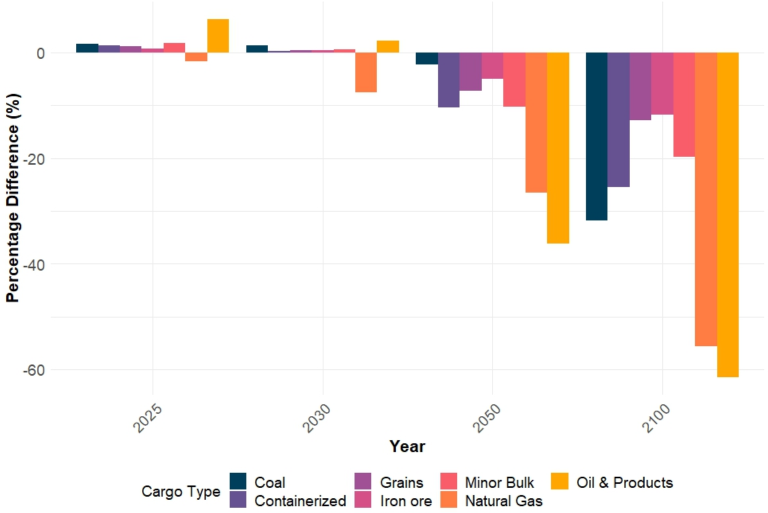

Figure 3.13.: Comparison of MIT-B-EU scenario with respect to baseline non-MIT scenario.

- **Regardless of the scenario or the level of carbon tax imposed, shipping demand is expected to rise across multiple regions.** Sub-Saharan Africa stands out with the most substantial growth due to economic and demographic expansion (Figure 3.14).

On the import side, China, Mexico, India, Canada, and LACA also show notable increases, but Sub-Saharan Africa outpaces them the all by end of the century. On the export side, Brazil and Oceania are projected to see expansion due to strong iron ore shipments and limited alternatives. LACA's diversified cargo exports and India & Mexico's focus on minor bulk cargoes further sustain overall trade growth. Because these trends persist across various scenarios, stakeholders can view these markets with higher certainty. Policymakers should prioritize investments in port infrastructure and strengthen regulatory frameworks to support these expansions. Industry leaders and investors can capitalize on the heightened certainty by adopting advanced logistics solutions and forging strategic partnerships.

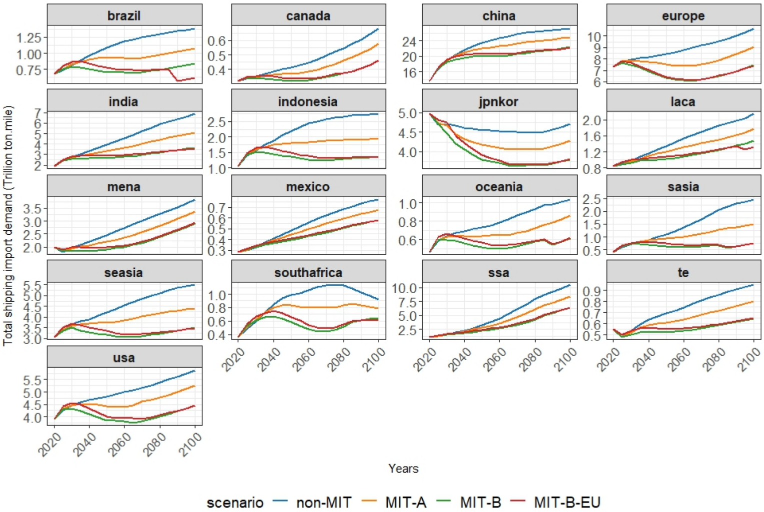

Figure 3.14.: Global seaborne trade in the scenarios breakdown by importing region.

- **China** maintains its upward trajectory as a major importing region across all scenarios. Its role as an exporter, particularly in minor bulk cargoes, continues to strengthen, even under mitigated scenarios. The **USA**'s position as an exporter remains resilient, though oil exports decline in mitigated scenarios. As an importer, the USA's trend—whether upward or downward—is highly dependent on the ambition level of policy measures. A similar pattern is observed in Southeast Asia, where import trends are also closely tied to policy severity.
- **Based on all scenarios, it is anticipated that coal trade will**

decrease over time, while there is a likelihood of an increase in the trade of grain, iron ore, containerized cargo, and minor bulk. As for LNG and oil products, there is a high level of uncertainty, and there are more observed fluctuations in response to the global carbon tax (Figure 3.15).

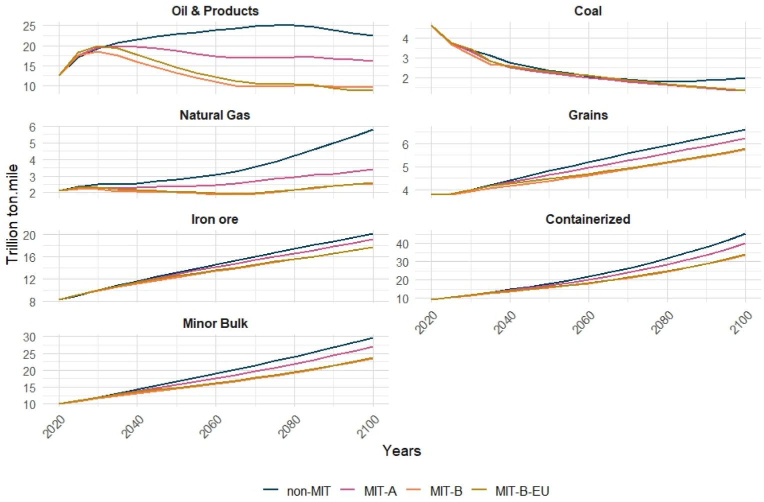

Figure 3.15.: Global seaborne trade in the scenarios breakdown by group of products.

- **Strengthening policy measures for decarbonization can deliver significant emissions reductions but must be balanced against potential economic impacts.** As shown in Figure 3.16, stricter decarbonization measures significantly raise policy costs and drive shipping demand declines beyond what GDP losses alone would suggest. This extra drop is due in part to reduced fossil fuel trade and higher fuel prices, not just slower economic growth. The trade-off between ambitious emission targets and economic impacts is clear: stricter policies lead to deeper emissions cuts but come with significant costs to global trade and economic activity.

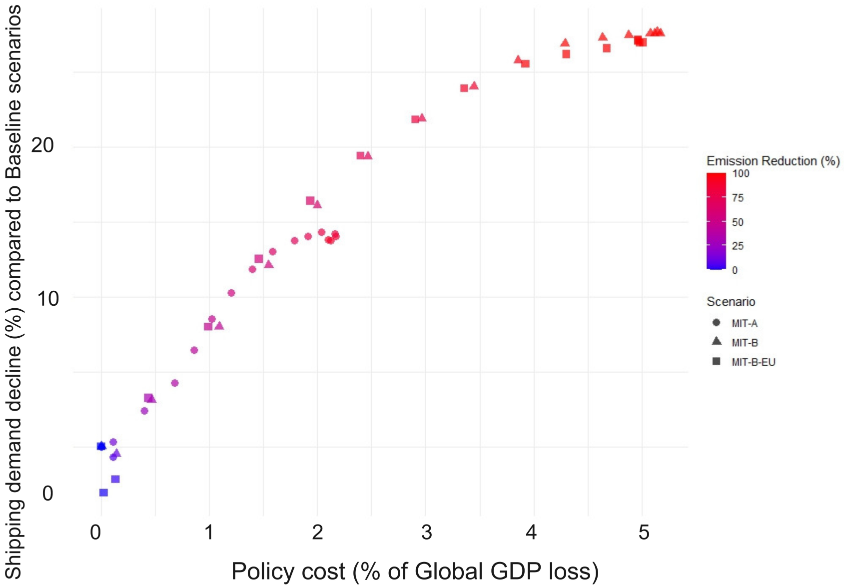

Figure 3.16.: Global policy costs, emission reduction, and shipping demand decline relationship.

Stricter taxation and the rising costs of clean technologies exert pressure on the overall economy and make it harder for smaller or less financially strong companies to enter the market. As a result, larger companies that can more easily bear these costs will likely gain an advantage in challenging market conditions. Additionally, as expenses and operational challenges increase, other shipping sectors may adopt business plans and strategies commonly used in the container shipping industry, such as standardizing processes and leveraging advanced technology, to remain competitive in this stressed market.

3.5. UNCERTAINTY AND FUTURE WORK

Scenarios and models inherently involve uncertainty due to their projective nature, as emphasized by [142], who differentiate between unrecognized knowledge gaps and acknowledged limitations. [143] categorize this uncertainty into key areas: context and framing, input, model structure, and parameter uncertainties. These uncertainties complicate the assessment of scenario projections as definitively right or wrong, suggesting that some elements may be less feasible than others. Rather than focusing on absolute values, such studies should prioritize identifying trends and understanding potential impacts, offering a more actionable and strategic perspective on future developments. These models should be viewed as comparative tools rather than purely predictive ones. Despite these inherent uncertainties, this study mitigates risks by validating against existing datasets while keeping the assumption of unchanged bilateral dynamics between regions. It focuses exclusively on changes driven by climate policy without altering other relationships. The emphasis remains on understanding broader patterns, not precise predictions, which can provide valuable insights into energy transition pathways and impacts.

Several recommendations are proposed to enhance the robustness and relevance of future studies. Firstly, there should be a greater focus on exploring new trade corridors, particularly those that may emerge for renewable fuels and other cargo types that are not currently prominent, such as hydrogen and biomass. This forward-looking approach will help identify and analyze emerging trends. Secondly, applying the econometric model across multiple Integrated Assessment Models could provide a more comprehensive multi-model analysis, enabling comparisons that yield deeper insights into trade dynamics. Lastly, it is interesting to investigate non-economic parameters, such as political instability, port regulations, and geopolitical tensions, to understand how these factors influence trade. This exploration will provide a more accurate understanding of trade patterns, but it falls outside the scope of this research.

Following this study, the next phase is to convert shipping demand into energy requirements. We aim to develop a fuel supply model that assesses the energy needs and fuel mix of the maritime industry, providing a more transparent view of shipping's contribution to the energy transition from an integrated perspective.

3.6. GLOBAL SCENARIO DEFINITION

This section is not included in the main manuscript of the published article. It is provided here to offer additional detail on the scenario definitions and assumptions used in this chapter.

Table 3.4 and figure 3.17 shows more details of the global scenarios used in the paper's analysis. The temperature increase is bound to end of the century (year 2100).

Table 3.4.: Scenarios and Carbon Tax Details for chapter 3

Scenario	**Carbon Tax** [$/tonCO2] **(2030, 2050, 2100)**	**Baseline** (Population & GDP)	**Temp (°C)**	**Mitigation Capacity**
Non-MIT	Global: (0, 0, 0)	SSP2	~3.5	Low
MIT-A	Global: (9, 52, 135)	SSP2	~2	Mid
MIT-B	Global: (36, 239, 673)	SSP2	~1.5	High
MIT-B-EU	Europe: (36, 239, 673) Others: (0, 239, 673)	SSP2	~1.5	High

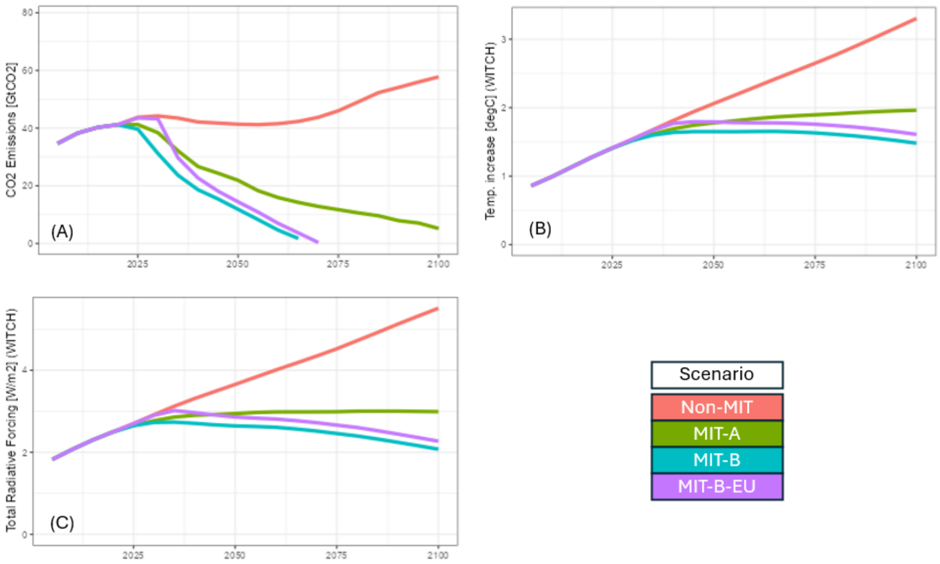

Figure 3.17.: Global projections under four scenarios. (A): Global CO_2 emissions ($GtCO_2$), showing the trajectory of emissions over time. (B): Temperature increase (°C) in the atmosphere, highlighting the impact of emissions on global temperature rise. (C): Total radiative forcing (W/m^2), representing the net effect of all climate forcing components. All panels compare the outcomes of the four scenarios included in the study (chapter 3).

4

ENERGY REQUIREMENT

This chapter translates projected shipping activity into consistent estimates of energy demand, fuel consumption, and fleet capacity across vessel types and sizes. Building on the endogenized trade and demand representation developed in the previous chapter, it introduces the physical and techno-economic mapping required to move from transport work to ships, engines, and fuels. In doing so, the chapter establishes the operational bridge between maritime trade dynamics and the global energy system.

By grounding shipping demand in vessel productivity, fleet composition, and fuel requirements, this chapter provides the necessary interface between demand-side projections and the integrated assessment of fuel choice, technology competition, and policy impacts that follows. It ensures that subsequent analyses of decarbonization pathways are anchored in realistic fleet dynamics and energy constraints rather than abstract demand assumptions.

4.1. INTRODUCTION

In the previous chapter, bilateral trade volumes for various cargoes were analyzed over time and across scenarios, measured in tons and ton-miles. However, tons and tons-miles cannot be directly translated into emissions, as ships of different sizes and types have varying emissions and operational profiles. As a result, before estimating shipping emissions, cargo must first be allocated to appropriate ship types and vessel sizes. This allocation is crucial because each ship type and size has its own fuel consumption rates, productivity levels, and specific investment costs. The energy estimation part involves three key components: (1) allocating shipping demand to vessel types based on cargo and assigning vessel sizes according to distance traveled and total demand to capture both current and future trends of cargo flow; (2) calculating the fuel consumption for each vessel size and type; and (3) estimating the productivity of each vessel category and size. By integrating these factors, the shipping industry's energy requirements across different scenarios can be estimated. Moreover, expanding shipping demand requires a larger fleet with more vessels, which demands significant investments in new shipbuilding. As we look to the future, investments in additional vessels should be considered. Ship capacities are inherently linked to transport demand on one side, while on the other, they determine fuel consumption, emissions, and the scale of investment required for fleet expansion. The transition to alternative fuels has a dual impact. It influences the operating costs associated with fuel production. It simultaneously increases capital expenditures for building technologically advanced vessels capable of operating on these fuels. By establishing this link between cargo demand, vessel characteristics, and the cost of newbuild ships, the actual energy needs of maritime transportation and the associated shipbuilding expense requirements can be estimated. This provides a foundation for projecting future shipping emissions from a bottom-up, holistic, and integrated perspective suitable for the climate mitigation context.

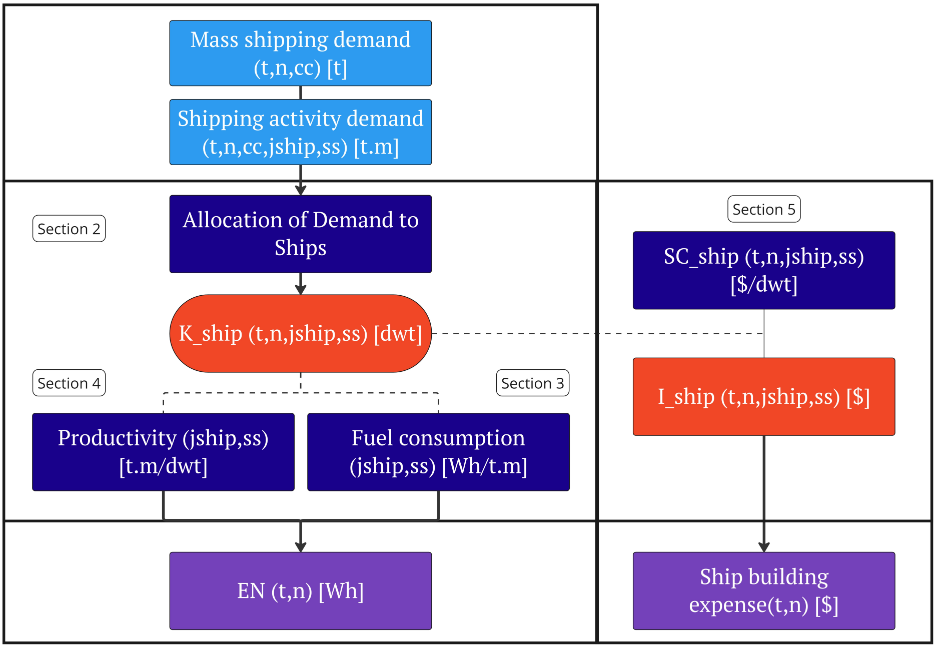

Figure 4.1.: Flow diagram of estimations done for this chapter.

Figure 4.1 presents the methodological framework used for this chapter to link cargo demand with fuel consumption and shipbuilding costs. The process begins with shipping mass demand and shipping activity demand, which quantify the required transportation in terms of tons and ton-miles. Since emissions cannot be inferred directly from these metrics, cargo is allocated to ship types and vessel sizes. This allocation determines the total deadweight capacity (K_{ship}), a key input for estimating fuel consumption and ship productivity. The fuel consumption values are used to calculate the total energy demand (EN), which forms the basis for emissions estimation. Additionally, the allocated deadweight capacity is used to estimate shipbuilding costs, considering ship specific cost (SC_{ship}) and total investment requirements (I_{ship}), which are different for different combinations of vessel types and sizes.

To ensure consistency throughout the analysis, two fundamental aspects are established and applied across all sections: the classification of vessel sizes and cargo mapping.

4.1.1. VESSEL SIZE CLASSIFICATION

Vessels are categorized into four size categories: small, medium, large, and ultra-large, and each category is treated distinctly. This categorization captures heterogeneity in capacities, thereby laying the foundation for subsequent vessel-size allocation. Vessel sizes are characterized by the deadweight tonnage (DWT). A set of bin edges is defined for each vessel type. The values are shown in the Table 4.1. A vessel with size index *ss* is then assigned to a discrete size category.

These bin ranges were selected based on detailed IMO report data and defined with two main considerations. First, reducing vessel sizes to four uniform bins creates a balanced distribution that avoids skewed groups, simplifying analysis while preserving proportional capacity shares. Second, the thresholds are aligned with key maritime chokepoints and operational conditions—such as the Panama and Suez Canal limits, port accessibility, and draft restrictions—that directly influence vessel design and routing. This approach captures the essential differences among tanker ships, bulk carriers, and container ships while reflecting the practical constraints and economic realities of global shipping, thereby enabling a straightforward and reliable approach.

Table 4.1.: Ship size categorization information.

Category	**TEU Range**	**DWT Range**	**Description / Examples**
Tanker ships			
Small	–	0–20,000	Coastal and mini tankers for short-haul and shallow-draft operations.
Medium	–	20,000–60,000	Handymax/LR1 vessels for regional and mid-distance trades.
Large	–	60,000–120,000	Panamax/Aframax vessels for major trade routes and canal transit.
Ultra-large	–	120,000+	Suezmax, VLCC, and ULCC vessels for long-haul intercontinental transport.
Bulk carriers			
Small	–	0–35,000	Handysize vessels for niche trades and shallow ports.
Medium	–	35,000–60,000	Handymax vessels balancing capacity and accessibility.
Large	–	60,000–80,000	Panamax vessels constrained by the old Panama Canal limits.
Ultra-large	–	80,000+	Capesize and larger vessels requiring deepwater terminals.
Container ships			
Small	0–2,000	0–18,560	Feeder vessels serving regional and smaller ports.
Medium	2,000–5,000	~18,560–46,400	Sub-Panamax vessels balancing capacity and flexibility.
Large	5,000–12,000	~46,400–111,360	Panamax and New Panamax vessels for main trade lanes.
Ultra-large	12,000+	~111,360+	ULCVs operating on deep-sea trunk routes.

4.1.2. CARGO TO VESSEL TYPE MAPPING

Although different cargoes may necessitate distinct vessel designs—for example, hydrogen carriers may require unique features that incur additional costs—our analysis employs a simplified cargo-mapping process. In this approach, cargo types *cc* are assigned to specific ship types *jship*: tankers for oil, oil products, LNG, and hydrogen; container ships for containerized cargo; and bulker carriers for iron ore, grains, and minor bulk goods. Deadweight tonnage (dwt) is used consistently across all vessels, including container ships, with conversions applied as necessary to ensure uniformity. Data from Clarkson's SIN database (1995–2024) provided a conversion factor between TEU and DWT, showing a stable range of 9.15–9.56 tons per TEU. Given the minor variation observed throughout this period, an average factor of 9.28 tons per TEU was adopted. This method captures the key differences in vessel requirements without unnecessary complexity, enabling adjustments to accommodate any specialized costs.

4.1.3. CORE EQUATIONS

The following are the core equations that relate the parameters and variables of the primary model. In this framework, the total shipping energy required in region n at time t is denoted by $EN_{t,n}$ (measured in TWh). Energy demand is determined by the fuel consumption rate $FC_{jship,t,n}$ (in TWh per million ton-miles), which is multiplied by the annual productivity of each vessel type, $\text{Productivity}_{jship,t,n}$ (in ton-miles per dwt.year), and by the active fleet capacity $K\text{ship(active)}_{jship,t,n}$ (in million deadweight tons, Mdwt). This relationship is captured in Equation (4.1):

$$EN_{t,n} = \sum_{jship} FC_{jship,t,n} \times \text{Productivity}_{jship,t,n} \times K\text{ship(active)}_{jship,t,n} \tag{4.1}$$

$K_{\text{ship(active)}}$ for vessel type $jship$ at time t and scenario n is estimated by dividing the aggregated shipping demand of the cargo types cc mapped to $jship$ by the productivity of that vessel type. It is shown in equation (4.2):

$$K\text{ship(active)}_{jship,t,n} = \frac{\sum_{cc \in \text{mapped to } jship} \text{Shipping Demand}_{cc,t,n}}{\text{Productivity}_{jship,t,n}} \tag{4.2}$$

In addition, the active fleet capacity is limited by the total fleet capacity available:

$$K\text{ship(active)}_{jship,t,n} < K\text{ship(total)}_{jship,t,n} \tag{4.3}$$

To capture the evolution of the fleet over time, ship depreciation and new investments are incorporated. The total fleet capacity in region n for ship type $jship$ at time $t+1$ is given by:

$$K\text{ship(total)}_{jship,t+1,n} = K\text{ship(total)}_{jship,t,n} \times (1-\delta_{\text{ship}})^{\Delta t} + \Delta t \times \frac{I_{jship,t,n}}{SC_{jship,t,n}} \tag{4.4}$$

$$\delta_{\text{ship}} = 1 - \exp\left(\frac{1}{-\text{lifetime}_{jship} + \frac{0.01}{2} \times \text{lifetime}^2_{jship}}\right) \tag{4.5}$$

Here, δ_{ship} represents the depreciation rate based on the ship's lifetime (25 years), as shown in equation (4.5). Δt is the model time step (five years), $I_{jship,t,n}$ is the investment in new ships (in T\$), and $SC_{jship,t,n}$ is the specific construction cost in T\$ per Mdwt.

Finally, the total cost of ship production in region n at time t is determined by summing the investments across all vessel types and adding maintenance costs, estimated via the coefficient φ as a fraction of ship capacity:

$$Cost_{t,n} = \sum_{jship} \left(I_{jship,t,n} + \left[K\text{ship(total)}_{jship,t,n} \times \varphi\right]\right) \tag{4.6}$$

Table 4.2.: Description of Parameters and Variables.

Symbol	**Type**	**Unit**	**Description**
EN	Variable	TWh	Total shipping energy required
FC	Parameter	TWh/million ton-miles	Fuel consumption rate for each vessel type
Productivity	Parameter	ton-miles/DWT.year	Annual productivity of each vessel type
Kship(active)	Parameter	million DWT	Active fleet capacity of ships
Kship(total)	Variable	million DWT	Total fleet capacity of ships
Shipping Demand	Parameter	million ton-miles	Shipping demand for cargo
δ_{ship}	Parameter	fraction/year	Depreciation rate of ships based on a 25-year lifetime
Δt	Parameter	years	Model time step (set to 5 years)
I	Variable	million USD	Investment in new ships
SC	Parameter	USD/DWT	Specific construction cost/DWT
$Cost$	Parameter	million USD	Total cost of ship production
φ	Parameter	fraction/year	Maintenance cost coefficient as a fraction of ship capacity

Table 4.3.: Index Definitions.

Index	**Explanation**	**What is Included**
jship	Ship types	tanker, bulker, container ship
t	Time step	1, 2, 3, . . .
n	Regions	USA, Europe, etc.
cc	Cargo category	oil, LNG, coal, iron ore, grains, minor bulk, containerized, hydrogen
ss	Ship size	small, medium, large, ultra-large

In summary, the model first links shipping demand (measured in million ton-miles) to vessel productivity (in ton.mile/dwt·year) and fleet capacity (both total and active, in dwt) as specified in Equations (4.3) and (4.2). The model then computes the total energy required by the shipping sector (Equation (4.1)). Next, fleet capacity is updated over time through depreciation and new investments (Equation (4.4)), and the total cost of ship production is quantified (Equation (4.5)). All parameters, variables, and indices used in the equations are shown in Table 4.2 and Table 4.3.

Following this introduction, the allocation of shipping demand to various vessel types and sizes will be discussed. Next, calculations of ship fuel consumption, productivity, and new-build cost will be examined. These sections will collectively connect the previous part of the work to the next.

4.2. ALLOCATION OF DEMAND TO SHIP SIZES

4.2.1. OBJECTIVE

The bilateral trade flow $qtrade_{t,nn,n,cc}$ represents the mass of cargo cc traded from region nn to region n at time t. To account for different sizes and trip durations, we want to convert this to $mtrade_{t,nn,n,cc,ss}$, introducing the index ss to differentiate vessel sizes doing the work. This is necessary because, as mentioned earlier, the relevant parameters vary with vessel size. Our data includes the demand for shipping activity and the mass of cargo. Thus, we distribute $qtrade$ to $mtrade$ based on the distance and total shipping demand from nn to n, allocating each to vessel sizes.

4.2.2. METHODOLOGY

The dataset for this study is derived from earlier research [144–146]. This dataset is used by a recently released report of IEA chapter on international shipping [147]. It begins with global country-to-country trade flows in value and weight, disaggregated to more than 3,380 subnational centroids using population weights from GADM and CIESIN [148]. These centroids are linked to nearby ports through a hinterland network that combines road, rail, and inland waterways data [149, 150]. In parallel, an AIS-based maritime network identifies about 1,400 ports and maps roughly 280,000 route connections by vessel type [151]. Vessel-specific details, such as handling costs, dwell times, and speeds, are then integrated into a cost function to simulate freight movement, with flows allocated using a capacity-constrained shortest path algorithm [148, 152–155]. Validation against official records at major transit points, such as the Suez and Panama Canals [156, 157], yields a dataset that includes origin, destination, vessel type, vessel size, sea distance, fuel consumption, and cargo capacity for 2019 and 2020 port-to-port movements.

This dataset is useful for our study because it explicitly links trade flows with the vessels used, detailing origin, destination, vessel type and size, travel distance, and fuel usage. Its construction from multiple high-quality sources and rigorous validation ensures that real-world shipping patterns and regional trade differences are accurately captured. This clear connection between cargo demand and vessel characteristics forms a strong basis for allocating the cargo demand to ship sizes and estimating fuel consumption.

Given this rich dataset, several modeling approaches could be applied. One approach would be to map vessel sizes directly to trade routes using historical data from 2019 and 2020. This method accurately reflects the observed vessel sizes and trade patterns for the base year but lacks the flexibility to capture future shifts. For example, regions with low current import volumes might rely on small ships; however, as demand grows, historical mappings would continue to assign small vessels even when larger ships become more economically feasible. Another approach would be to employ regression models to predict a single ship size for each route as a function of distance and shipping demand. However, this one-to-one method fails to capture the real-world diversity of vessels operating on any given route, where a variety of ship sizes typically exist rather than a single size. These two approaches and ideas are rooted in classical economic shipping models and are appreciated by standard models [158, 159].

To overcome these limitations, an approach is developed that combines distance and shipping demand to estimate the distribution of ship sizes. This method divides the base-year shipping demand into four quantiles and categorizes route distances into six ranges. This segmentation results in 24 distinct blocks (Figure 4.2, each representing a unique combination of demand and distance. For each block, the distribution of ship sizes is estimated from the observed data, assuming that these distributions remain applicable in future scenarios. This method effectively captures the natural spectrum of vessel sizes used across different routes while accommodating shifts in overall demand, thus providing a robust and realistic modeling framework.

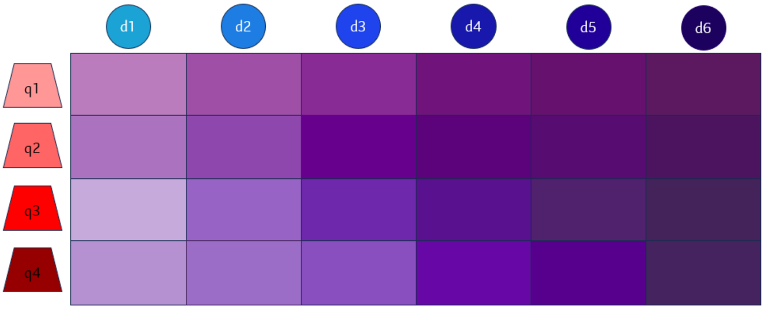

Figure 4.2.: Divided blocks of demand and distance combination to estimate ship size shares.

REGIONAL MAPPING AND DATA PREPROCESSING

The dataset presents data at the port-to-port level. First, each port is mapped to its corresponding country. Then by mapping each country, identified via ISO3 codes, to a predefined region using a mapping function $\rho : \mathcal{C} \rightarrow \mathcal{R}$, where $\mathcal{C}$ is the set of ISO3 country codes and $\mathcal{R}$ is the set of regional labels (e.g., `canada`, `europe`). This mapping facilitates the aggregation of route data at the regional level. For each vessel type, capacity thresholds are computed from the empirical distribution of total shipping demand between each pair of regions (in metric tons). Let q_1, q_2, and q_3 denote the 25th, 50th, and 75th percentiles, respectively. A quartile label is assigned to any route via the mapping function based on its aggregated cargo capacity C.

$$\phi(C) = \begin{cases} Q_1, & \text{if } C \leq q_1, \\ Q_2, & \text{if } q_1 < C \leq q_2, \\ Q_3, & \text{if } q_2 < C \leq q_3, \\ Q_4, & \text{if } C > q_3. \end{cases}$$

Table 4.4.: q_i parameters for creating distribution blocks.

Vessel Type [m.tons]	**q1**	**q2**	**q3**
Container ship	0.561	1.547	5.529
Bulker	0.756	3.522	12.274
Tanker	0.300	1.660	7.585

Distances between origin and destination ports are initially provided in kilometers and converted to nautical miles using a conversion factor $\alpha = 0.539957$. The transformed distance d is then categorized into one of six intervals from $d1$ to $d6$ (nautical miles) of

$$[0, 1000),\ [1000, 3000),\ [3000, 5000),$$
$$[5000, 7000),\ [7000, 9000),\ [9000, \infty)$$

Six distance intervals are chosen to capture the practical differences in shipping routes and vessel operations. The first interval, covering 0–1000 nautical miles, represents short-haul, coastal, and intra-regional trades—for example, routes from Indian ports to Karachi in Pakistan. The second interval, spanning 1000–3000 nautical miles, reflects regional trades such as those connecting Indonesia to Chinese ports. The third interval, from 3000 to 5000 nautical miles, includes medium-distance journeys such as routes from the Middle East to Indonesia via the Hormuz Strait and the Indian Ocean. The fourth interval, between 5000 and 7000 nautical miles, captures longer transoceanic passages, as seen on routes from the USA's west coast to China through the Pacific Ocean. The fifth interval, spanning 7000–9000 nautical miles, characterizes extended voyages, such as the Mexico–Russia route via the Panama Canal. Finally, the sixth interval, for distances exceeding 9000 nautical miles, corresponds to ultra long-haul trades, exemplified by the route from Rotterdam (Netherlands) to Australian ports. This interval encompasses major intercontinental shipping lanes, where vessel performance, fuel consumption, and operational planning vary significantly. This segmentation distinguishes the operational characteristics of different routes and provides a framework for estimating the distribution of ship sizes across diverse trading lanes.

Next, the observed cargo capacities are aggregated for each route r, defined by vessel type *jship* and a pair of origin and destination regions. Denote the aggregated capacity on route r by

$$C(r) = \sum_{i \in \mathcal{I}_r} c_i, \tag{4.7}$$

where $\mathcal{I}_r$ is the set of trips on route r and c_i is the capacity of trip i. Based on $C(r)$, the route is assigned a capacity quartile label. The data are then grouped by vessel type, capacity quartile, distance category, and vessel size category. Let $S_{jship,q,d,ss}$ denote the total capacity for vessel type *jship*, quartile q, distance category d, and size category ss. The percentage share for each size category ($p_{jship,q,d,ss}$)is computed as:

$$p_{jship,q,d,ss} = \frac{S_{jship,q,d,ss}}{\sum_{ss'} S_{jship,q,d,ss'}} \times 100, \tag{4.8}$$

Yielding a normalized measure of the proportion of each vessel size within the corresponding subgroup. To thoroughly validate the approach, the dataset is randomly split into 80% training and 20% test sets across five iterations using a 5-fold cross-validation procedure, and the performance metrics are averaged over these iterations.

Then using Equation 4.9 we distribute q_{trade} to m_{trade}.

$$\begin{aligned} m\text{trade}_{t,nn,n,cc,ss} &= q\text{trade}_{t,nn,n,cc} \times p_{jship,q,d,ss} \\ &\text{if} \sum_{cc \in \mathcal{C}_{jship}} q\text{trade}_{t,nn,n,cc} \in [q, d] \end{aligned} \tag{4.9}$$

The allocation of vessel sizes reflects real-world fleet composition, facilitating further estimations of energy requirements and shipbuilding investment. This framework balances simplicity and granularity, creating a robust and computationally efficient tool for modeling maritime shipping dynamics. Once the distribution of ship sizes is known, it can be connected to each ship's productivity and fuel consumption to estimate the total energy requirement and the new shipbuilding investment.

4.2.3. RESULTS

Figure 4.3, Figure 4.4, Figure 4.5, and Table 4.5 present the probability distributions of vessel sizes across distance ranges for bulk carriers, tanker ships, and container ships, averaged over five combinations of train/test splitting data.

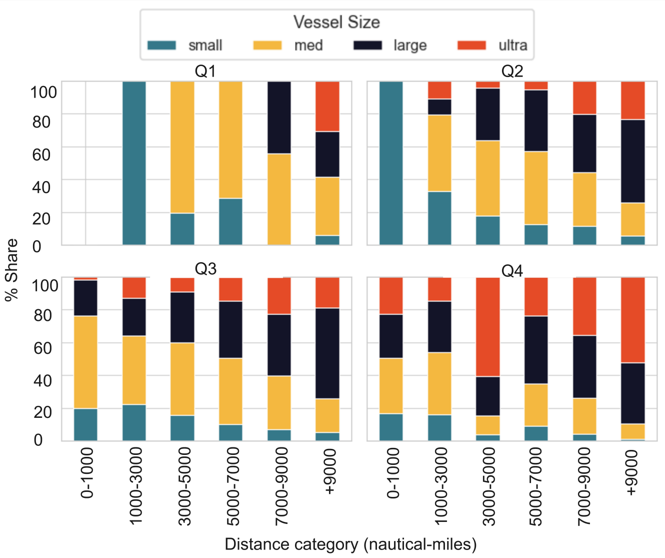

Figure 4.3.: Share of each size of vessels carrying in a specified range for bulk carriers.

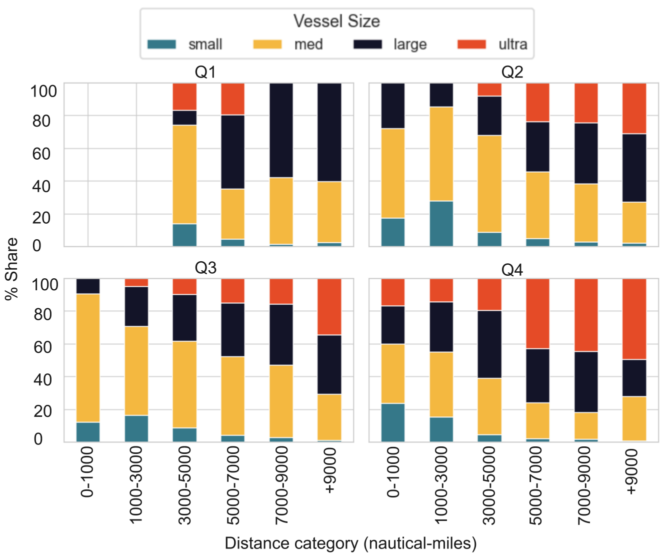

Figure 4.4.: Share of each size of vessels carrying in a specified range for tanker ships.

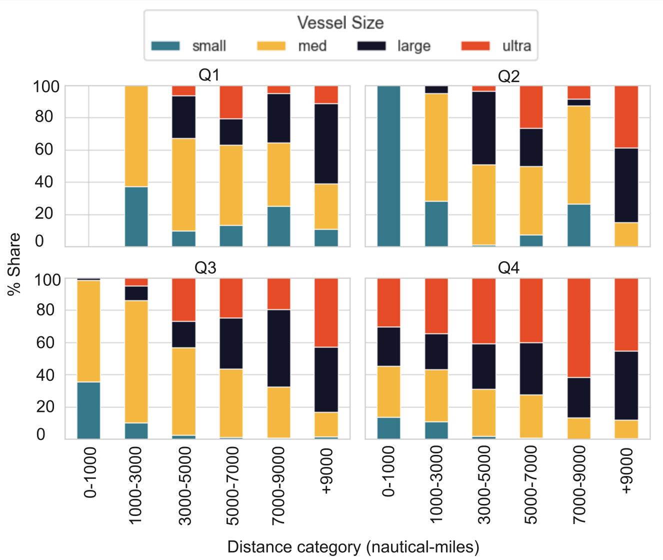

Figure 4.5.: Share of each size of vessels carrying in a specified range for container ships.

Figure 4.9, Figure 4.10, Figure 4.11, and Table 4.5 demonstrate that vessel sizes are distributed according to shipping distance and demand levels for bulk carriers, tankers, and container ships. Smaller vessels dominate shorter routes and lower-demand segments, whereas larger vessels are more common on longer, high-demand routes. This pattern reflects the operational and economic rationale in maritime transport: smaller vessels offer lower costs and better access to smaller ports, making them ideal for frequent, short-haul trips, whereas larger vessels achieve economies of scale that reduce per-unit costs over long distances. Specifically, container ships exhibit a notable shift, with smaller ships prevalent on 1000–3000 nautical-mile routes and ultra-large vessels increasingly used beyond 7000 nautical miles in high-demand quartiles. Although larger vessels are favored on major dry bulk shipping corridors, medium and small bulkers remain significant where port limitations apply. Tankers also differ by cargo type; very large crude carriers dominate long-haul, high-demand routes, whereas smaller product tankers serve regional or specialized trades. Overall, the observed trends validate expectations based on maritime shipping economics. The progressive shift from smaller to larger vessels with increasing distance and demand is consistent across all vessel types.

Table 4.5.: Distribution of Vessel Size by Route Characteristics % ($p_{jship,q,d,ss}$).

Q	Distance	small	med	large	ultra-large
Container					
Q1	1000-3000	37.37	62.63	0.00	0.00
	3000-5000	9.75	57.44	26.40	6.41
	5000-7000	13.34	49.61	16.54	20.51
	7000-9000	25.02	39.51	30.50	4.97
	9000+	10.75	28.14	49.97	11.14
Q2	0-1000	100.00	0.00	0.00	0.00
	1000-3000	28.29	66.66	5.05	0.00
	3000-5000	1.25	49.46	45.81	3.48
	5000-7000	7.34	42.58	23.62	26.46
	7000-9000	26.66	60.57	4.15	8.61
	9000+	0.00	14.88	46.48	38.64
Q3	0-1000	35.74	62.90	1.36	0.00
	1000-3000	10.38	75.53	9.11	4.98
	3000-5000	2.57	54.12	16.49	26.82
	5000-7000	1.15	42.56	31.59	24.69
	7000-9000	0.77	31.84	47.93	19.45
	9000+	1.55	15.35	40.42	42.67
Q4	0-1000	13.72	31.62	24.47	30.18
	1000-3000	11.05	32.27	22.06	34.62
	3000-5000	1.77	29.45	28.03	40.75
	5000-7000	0.89	26.73	32.31	40.08
	7000-9000	0.19	13.35	24.85	61.61
	9000+	0.56	11.32	42.79	45.32
Dry bulk					
Q1	1000-3000	100.00	0.00	0.00	0.00
	3000-5000	19.50	80.50	0.00	0.00
	5000-7000	28.49	71.51	0.00	0.00
	7000-9000	0.00	55.74	44.26	0.00
	9000+	6.00	35.51	27.66	30.83
Q2	0-1000	100.00	0.00	0.00	0.00
	1000-3000	32.85	46.39	9.94	10.82
	3000-5000	17.82	45.77	32.09	4.32
	5000-7000	12.49	44.58	37.75	5.18
	7000-9000	11.42	32.95	35.48	20.16
	9000+	5.53	20.15	50.93	23.39
Q3	0-1000	19.88	56.29	21.92	1.90
	1000-3000	22.38	41.89	22.88	12.85
	3000-5000	15.76	44.35	30.93	8.96
	5000-7000	10.33	40.19	34.98	14.49
	7000-9000	7.01	32.94	37.43	22.62
	9000+	5.43	20.37	55.54	18.66
Q4	0-1000	16.90	33.58	26.74	22.79
	1000-3000	16.03	38.01	31.30	14.66
	3000-5000	3.91	11.67	24.04	60.38
	5000-7000	9.31	25.78	41.29	23.62
	7000-9000	4.19	22.12	38.10	35.60
	9000+	1.23	9.30	37.40	52.06
Tanker					
Q1	3000-5000	14.11	60.16	9.00	16.73
	5000-7000	4.50	30.66	45.39	19.45
	7000-9000	1.56	40.50	57.93	0.00
	9000+	2.61	37.17	60.22	0.00
Q2	0-1000	17.31	54.86	27.83	0.00
	1000-3000	27.75	57.63	14.62	0.00
	3000-5000	8.66	59.34	23.90	8.11
	5000-7000	5.12	40.59	30.72	23.58
	7000-9000	2.85	35.42	37.45	24.28
	9000+	2.26	24.85	41.80	31.09
Q3	0-1000	12.22	78.23	9.55	0.00
	1000-3000	16.37	54.31	24.36	4.97
	3000-5000	8.88	52.72	28.65	9.75
	5000-7000	4.48	47.68	32.90	14.93
	7000-9000	3.02	44.05	37.37	15.57
	9000+	1.35	28.05	36.05	34.54
Q4	0-1000	23.88	36.14	23.31	16.68
	1000-3000	15.57	39.70	30.28	14.45
	3000-5000	4.70	34.57	41.24	19.50
	5000-7000	2.40	21.83	32.92	42.85
	7000-9000	1.84	16.35	37.33	44.49
	9000+	0.91	27.14	22.56	49.38

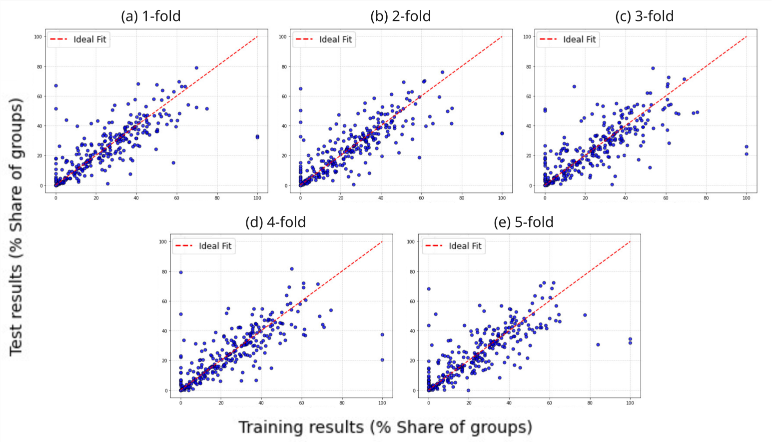

Figure 4.6.: Five k-fold cross-validation plots.

Figure 4.6 shows the validation plots of each cross-validation done to observe the fitness of the training to the test data.

4.3. FUEL CONSUMPTION ANALYSIS

4.3.1. OBJECTIVE

This section estimates fuel consumption per transport work unit for different vessel types and sizes. The aim is to calculate average fuel consumption values that can be used in Equation 4.3 to inform energy demand modeling.

4.3.2. APPROACH

The dataset provides the fuel consumption for a trip in tons. Dividing this value by the product of the actual cargo capacity (in tons) and the trip distance (in nautical miles) yields the fuel consumption in tons of fuel per ton-mile. To express this metric in energy terms (Wh/ton-mile), the fuel consumption shares by fuel type for 2019 and 2020 are incorporated as described in [160], along with the corresponding calorific values from [161]. The fuel calorific values and shares are summarized in Table 4.6.

Table 4.6.: Fuel Properties and shares for 2019 and 2020.

Fuel	**Share in 2019**	**Share in 2020**	**Calorific Value [kWh/kg]**
Heavy Fuel Oil (HFO)	0.810	0.496	11.61
Light Fuel Oil (LFO)	0.031	0.323	12.22
Diesel/Gas Oil	0.113	0.121	12.75
Liquefied Natural Gas (LNG)	0.047	0.059	15.33

The weighted average calorific value for each year is computed as:

$$\overline{\mathrm{CV}} = \sum_f s_f \, \mathrm{CV}_f, \tag{4.10}$$

where s_f is the fractional share of fuel type f and CV_f is the corresponding calorific value in kWh/kg. The energy-based fuel consumption is then determined by

$$FC_{jship}[\text{Wh/ton-mile}] = \left(\frac{\text{Fuel consumption (tons)}}{\text{Cargo capacity (tons)} \times \text{Distance (nm)}}\right) \times 10^6 \, \overline{\mathrm{CV}}, \tag{4.11}$$

where the factor 10^6 accounts for converting tons to kilograms (1 ton = 1000 kg) and kWh to Wh (1 kWh = 1000 Wh). This formulation yields an energy-based metric of fuel consumption in Wh per ton-mile.

4.3.3. RESULTS

Using the aforementioned approach, fuel consumption for each vessel type and size category was calculated from actual operational data. A weighted average based on the capacity share of actual sizes is then used in each category.

Table 4.7.: Fuel Consumption by Vessel Type and Size Category.

Vessel type	Vessel size	Fuel Consumption [Wh/ton.mile]
Bulk carrier [DWT]	0–35k (small)	48.002
	35–60k (medium)	32.440
	60–100k (large)	25.088
	>100k (ultra-large)	16.671
Container ship [TEU]	0–3k (small)	90.994
	3–8k (medium)	68.246
	8–12k (large)	55.280
	>12k (ultra-large)	37.008
Tanker ship [DWT]	0–20k (small)	99.497
	20–60k (medium)	46.802
	60–120k (large)	39.657
	>120k (ultra-large)	25.228

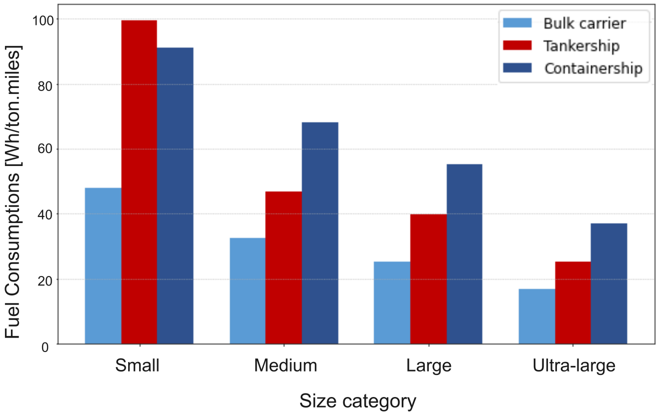

Figure 4.7.: Averaged fuel consumption of different vessel types and sizes.

The results are consistent with established maritime research. A clear trend of decreasing fuel consumption per ton-mile with increasing vessel size is observed, consistent with economies of scale, in which larger ships achieve better energy efficiency for the same cargo capacity [162, 163]. The higher consumption in container ships likely reflects faster service speeds and more complex operational requirements, while the comparatively lower values in Bulk carriers are associated with simpler configurations and slower speeds. The complete results are shown in Table 4.7 and Figure 4.7.

4.4. PRODUCTIVITY OF SHIPS

4.4.1. OBJECTIVE

This section evaluates the productivity of ships of various types and sizes. Productivity is expressed in units of [ton-mile/dwt.year]. It shows the average transport work that could be performed per unit of dwt vessel size in a year across different vessel categories, including tankers, bulk carriers, and container ships. The calculations are based on real-world data from the Fourth IMO GHG Study, ensuring that the derived metrics accurately reflect operational performance. These productivity values serve as critical inputs to emissions modeling, as shown in Equation 4.2 and Equation 4.1.

4.4.2. APPROACH

Productivity values specific to vessel types and size categories were derived from the IMO Fourth GHG Study (2020) and additional sources. These productivity metrics, measured in [ton-mile/dwt.year], reflect the operational efficiency of vessels. To align with the size categories defined in this study, we calculated weighted average productivity values for each vessel size category based on the productivity values reported by IMO for individual vessel sizes and their respective capacity shares within the category [4, pp. 170–172]. For example, the small-size category for container ships includes vessels with dwt of 0–1k, 1–2k, and 2–3k, which have IMO-reported productivities of 42, 47, and 64.2 [ton-mile/dwt].year], respectively. Using their capacity shares (0.3091, 0.4545, and 0.2364), the weighted-average productivity for the small-size category is calculated as 49.52 [ton-mile/dwt.year]. This approach is applied consistently across all vessel types and size categories, ensuring that the derived productivity values accurately represent the operational characteristics of each category.

4.4.3. RESULTS

This section reveals clear productivity distinctions across vessel types and sizes, aligning with their operational profiles. Container vessels exhibit the highest productivity due to optimized routing and efficient cargo handling. Bulk carriers exhibit stable productivity across vessel sizes, reflecting consistent operational patterns, whereas tankers show a moderate increase in productivity with vessel size. Larger ships are typically assigned to major routes with high cargo volumes and well-developed port infrastructure, which allows them to sail with fuller loads and turn around more quickly. Because of these steady flows and efficient port handling, the time spent waiting or underutilized is reduced. As a result, each unit of a larger vessel's deadweight can transport more ton-miles of cargo over the course of a year.

Table 4.8.: Productivity of ships.

Vessel type	Vessel size [dwt, teu]	Size category	Capacity share in size category	Productivity [kton.mile/dwt]	Corrected Productivity [kton.mile/dwt]
Container ship	0-1k	Small	0.31	42	49.52
	1-2k		0.45	47	
	2-3k		0.24	64.2	
	3-5k	Medium	0.59	63.2	65
	5-8k		0.41	67.6	
	8-12k	Large	1	67.5	67.5
	12-14.5k	Ultra-large	0.57	67.6	67.6
	>14.5k		0.43	N/A	
Bulker	0-10k	Small	0.25	32.5	35.13
	10-35k		0.75	36	
	35-60k	Medium	1	36	36
	60-100k	Large	1	36.2	36.2
	100-200k	Ultra-large	0.69	40.4	41.41
	>200k		0.31	43.7	
Tanker	0-5k	Small	0.49	23.8	22.61
	5-10k		0.25	21.6	
	10-20k		0.25	21.3	
	20-60k	Medium	1	23.1	23.10
	60-80k	Large	0.24	25.8	27.17
	80-120k		0.76	27.6	
	120-200k	Ultra-large	0.26	28.2	35.08
	>200k		0.74	37.5	

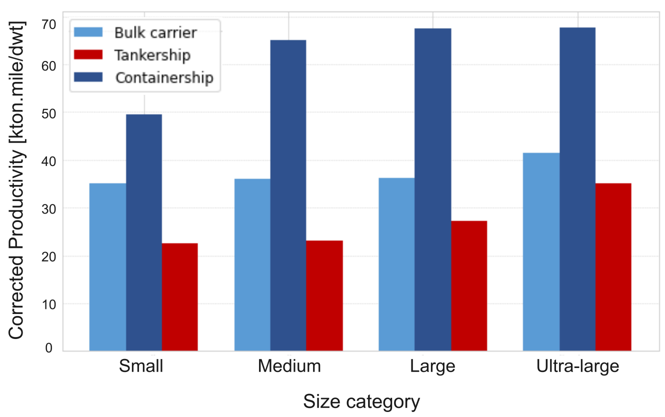

Figure 4.8.: Productivity levels of different vessel types and sizes.

Table 4.8 and Figure 4.8 show the detailed productivity results of different ships and sizes.

4.5. NEW-BUILD COST ANALYSIS OF SHIPS

4.5.1. OBJECTIVE

This part estimates the cost per deadweight ton (dwt) for different vessel types (tankers, bulk carriers, and container ships) using historical new-build ship price data. By examining the relationship between ship size (dwt) and cost, we aim to derive a cost function to support further economic assessments and comparisons across vessel types.

4.5.2. APPROACH & RESULTS

Data on new-build ship costs, including year of build, ship type, cost in millions of USD, deadweight tonnage (dwt), and cost per dwt, were obtained from multiple sources, and all prices were converted to 2005 USD and adjusted for inflation. The datasets, drawn from academic publications and reports [164–169] as well as Clarkson's contract reports [170–172], were combined into a single dataset. A 5-fold cross-validation procedure was then implemented, in which the data were randomly split 5 times into 80% training and 20% test sets, and the average performance metrics were computed.

After compiling the dataset, a log-log linear regression was performed for each ship type, with cost as a function of dwt, yielding a cost-per-dwt function for tankers, bulk carriers, and container ships. This method is adopted to represent the dominant size–cost scaling while avoiding unnecessary parameterization. While shipping market cycles also impact new-build prices, this factor is beyond the scope of our study. The focus is on the relationship between cost and size across a comprehensive dataset spanning multiple periods. The results give us the $SC_{jship,t,n}$ to be used in Equation 4.4. The regression model used is given by:

$$\log(\text{Cost}) = \alpha \cdot \log(\text{dwt}) + \beta \tag{4.12}$$

where α is the coefficient and β is the intercept. The results for each ship type are shown in Table 4.9.

Table 4.9.: Vessel cost-model results.

Vessel type	α	β	Avg. R^2 Training	MAE	RMSE
Tanker ship	-0.471	11.598	0.629	101.5	130.3
Bulk Carrier	-0.490	11.525	0.381	122.2	154.6
Container ship	-0.317	10.426	0.577	138.5	169.1

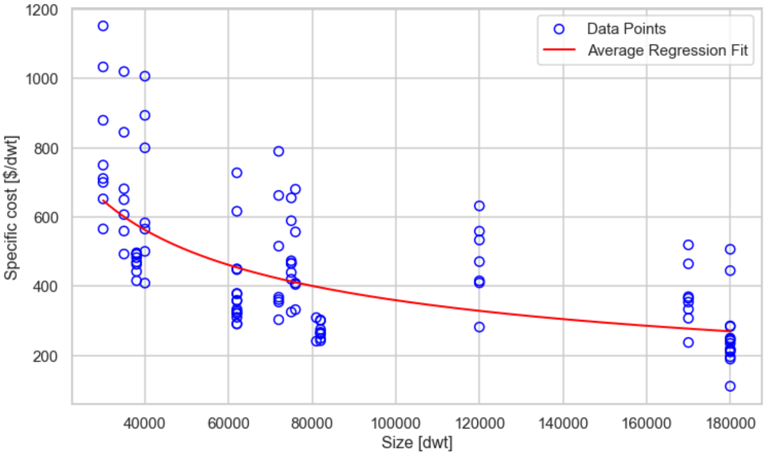

Figure 4.9.: Regression result for bulk carriers build cost per dwt.

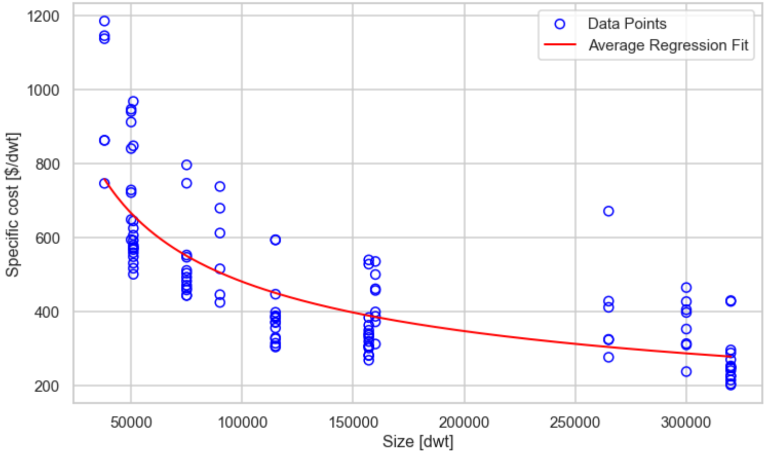

Figure 4.10.: Regression result for tankers build cost per dwt.

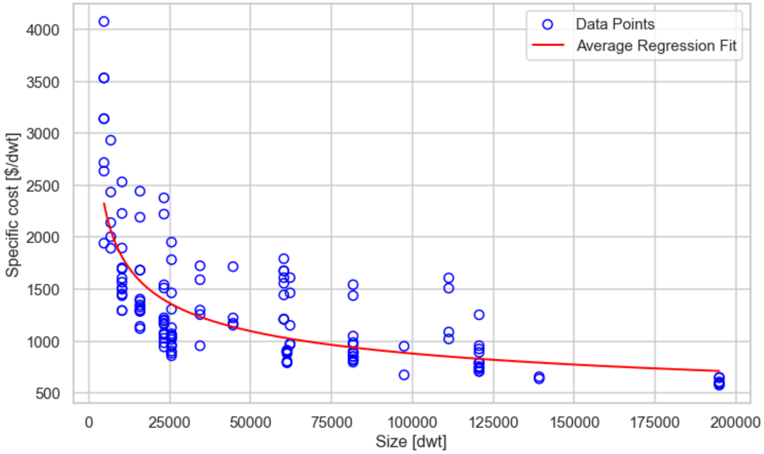

Figure 4.11.: Regression result for container ships build cost per dwt.

The regression analysis yielded distinct cost-per-dwt models for each ship type (Figures 4.9, 4.10, and 4.11), with tankers showing the highest explanatory power $(R^2 \approx 0.63)$, followed by container ships $(R^2 \approx 0.58)$ and then bulk carriers $(R^2 \approx 0.38)$. Tankers and bulk carriers exhibited almost similar slope coefficients, indicating that costs decrease with increasing ship size (dwt) at a relatively comparable rate. Container ships, however, showed a less negative slope, suggesting a more moderate decrease in cost with size. It should be noted that these estimates are based on conventional engine vessels and do not include additional costs associated with ammonia-derived engines or other alternative fuels. In the following chapters, this will serve as the baseline cost for diesel-engine vessels, and any additional costs associated with modifications for alternative fuels will be added to this base cost.

4.6. CONCLUSION

This chapter established the linkage between maritime shipping demand in ton-miles and the associated energy requirements. The allocation of shipping demand across ship types and sizes enabled the quantification of energy consumption in maritime transportation. Empirical vessel size distributions, derived from detailed operational data, were used to link cargo demand to corresponding vessel sizes and types. Fuel consumption analysis highlighted clear trends in vessel size and type, reflecting operational efficiency and economies of scale. Furthermore, vessel productivity metrics were systematically estimated, ensuring robust representation of real-world vessel performance. Additionally, analyzing new-build ship costs provided foundational cost models that illustrated the relationships between vessel size and construction expenses. Although these estimates are based on conventional vessels with traditional engines, they constitute an essential baseline for subsequent modeling, including the additional costs associated with alternative-fuel technologies. The findings from this chapter enable a comprehensive evaluation of maritime shipping's energy needs and shipbuilding investments, offering crucial insights into trade flow dynamics and decarbonization policies. Following this analysis, techno-economic modeling of alternative maritime fuels will be conducted. This subsequent phase involves regional optimization modeling of maritime fuel mixes, informed by the estimated energy requirements established here. Furthermore, the incremental costs of constructing new vessels capable of operating on alternative fuels will be considered, thereby bridging the gap between energy demand projections and viable decarbonization pathways in maritime shipping.

5

ENERGY SUPPLY AND EMISSION

This chapter examines how fuel choice, technology deployment, and emissions from international shipping evolve when maritime transport is embedded within an integrated energy–economy system. Building on the demand representation and physical energy requirements established in the preceding chapters, it introduces the WITCH-shipping model to analyse competition for fuels, technology learning, investment dynamics, and the interaction between economy-wide climate policy and sector-specific regulation. This chapter, therefore, represents the point at which shipping decarbonization is assessed as a system-level outcome rather than a sectoral exercise.
This chapter is currently *under review* at *Nature Communications*. Its analysis provides the central results of the thesis, linking trade-driven demand, fleet dynamics, and fuel availability to emissions pathways and policy effectiveness, and setting the stage for the regional differentiation examined in the following chapter.

5.1. INTRODUCTION

Maritime shipping is a cornerstone of global trade, moving over 80% of world cargo by volume and more than 70% by value [52, 53]. The sector emits about 1.0 $GtCO_2$ annually, or roughly 2.8% of global CO_2 emissions, with international shipping responsible for most of that total [4, 173]. Although the Paris Agreement did not directly assign emission targets to international shipping and aviation [81], the Kyoto Protocol mandated that the International Maritime Organization (IMO) regulate these sectors [82]. Long vessel lifetimes, the dependence on liquid fuels, and the limited feasibility of direct electrification make shipping a hard-to-abate sector [174]. The IMO's regulatory framework has gradually evolved from design and operation-based efficiency measures such as the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Ship Energy Efficiency Management Plan (SEEMP), and Carbon Intensity Indicator (CII) toward long-term decarbonization [4, 10, 12, 32, 83]. The 2023 IMO GHG Strategy sets a net-zero lifecycle ambition by or around 2050, with interim checkpoints for 2030 and 2040 [175]. In April 2025, the 83rd session of the Marine Environment Protection Committee (MEPC 83) approved a mid-term basket of measures that combines a global well-to-wake GHG fuel intensity standard with a pricing mechanism; although implementation was recently postponed, and final details remain under negotiation. [176, 177]. While efficiency measures can reduce emissions, they are insufficient to deliver deep decarbonization [178]. Achieving net zero will depend on the large-scale deployment of zero and near-zero GHG fuels and supporting infrastructure, yet the pace and cost of this transition remain uncertain [4, 179]. The feasibility of meeting this 1.5 °C-aligned target depends on scalable zero-carbon fuels, yet the most promising option, ammonia, remains controversial due to safety concerns, toxicity, and port-side deployment challenges [180]. As maritime activity remains closely tied to global economic growth, emissions are likely to increase in the absence of viable fuel alternatives [39, 181, 182].

The literature on maritime decarbonization can be divided into two main strands. Qualitative assessments compare alternative marine fuels such as hydrogen, ammonia, methanol, and biofuels based on technical feasibility, safety, cost, and environmental performance, and they converge on the view that no single fuel suits all ship types and routes. However, these studies lack explicit forward-looking scenarios and pathways [183–187]. Quantitative scenario analyses provide valuable insights but often treat shipping in isolation from the broader energy system, limiting understanding of upstream competition for clean fuels and downstream consequences for land use and fuel availability [181, 188–194]. Studies that do include broader economic interactions often focus on specific regions, aggregate all transport modes, or provide limited technological detail for maritime mitigation, and some examine only a single alternative fuel [195–210]. Shipping remains underrepresented in many integrated assessment exercises, constraining policy-relevant insights [211].

As policy ambition accelerates, the limitations of current studies and the simplified representation of shipping in integrated assessment models highlight the need for an approach that links international maritime shipping with the broader energy and climate system [211].

To address a corner of this gap, we integrate a detailed maritime shipping module into the WITCH integrated assessment model, which allows shipping activity, technology choice, and fuel use to be evaluated consistently within the broader energy, economy, and climate system. WITCH is a global and long-term optimization model that has been widely used in assessments connected to the IPCC and the broader literature, and it is well established for analysing mitigation pathways across multiple world regions [1, 134, 212]. The maritime module connects cargo-specific bilateral trade with vessel classes and size segments, fuel and engine options, and upstream production of alternative fuels, which ensures consistency in costs, resource use, and emissions across the entire economy. To examine how climate-budget constraints, sector-specific regulation, and ammonia availability shape maritime decarbonisation pathways, we develop six scenarios that vary accordingly (Table **??**). The *baseline* scenario represents a continuation of current policies and technological trends without climate constraints or maritime regulation. The 1.5 °C scenario imposes a global carbon budget consistent with limiting end of century warming to 1.5 °C, providing a view of how shipping evolves in a deeply decarbonized world. The 1.5 °C scenario with an IMO requirement adds a complete sectoral decarbonization target for shipping by 2050 and reveals the system-wide implications of meeting the highest level of ambition set by the IMO. A mitigated scenario with no possibility to use ammonia in shipping tests the consequences of excluding this fuel, which is one of the main candidates for long-range maritime transport, but remains controversial due to safety concerns and toxicity. Two additional scenarios apply the Net-Zero Framework that was proposed at MEPC-83 session, under both baseline and 1.5 °C conditions. Sectoral pricing starts as early as 2025 to assess the effectiveness of this emerging regulatory package from a system-wide perspective. Across all scenarios, shipping may use oil-based fuels, liquefied natural gas, biofuels, synthetic diesel, methanol, ammonia, or hydrogen for short-range applications, and learning effects for electrolyzers influence the cost of hydrogen-derived fuels. We also include sensitivity analysis of results to uncertainty in electrolyser cost-reduction rates and the timing of MEPC policy implementation. All results are reported on a well-to-wake basis, and emissions refer to CO_2 unless otherwise stated.

Table 5.1.: Scenario setup configuration. IMO refers to scenarios aligned with the International Maritime Organization’s 2050 net-zero target. MEPC denotes shipping-specific carbon pricing consistent with decisions of the IMO Marine Environment Protection Committee; NA indicates scenarios in which ammonia is excluded as a marine fuel.

Scenario	*Global policy*	*Shipping taxation*	*Ammonia ban*	*IMO2050 target*
baseline (BAU)	No policy	No	No	No
1.5 °C	Carbon budget	No	No	No
1.5 °C_IMO	Carbon budget	No	No	Yes
1.5 °C_NA	Carbon budget	No	Yes	No
baseline_MEPC	No policy	Yes	No	No
1.5 °C_MEPC	Carbon budget	Yes	No	No

This study delivers two principal contributions. First, it introduces a major methodological advancement to the WITCH integrated assessment model by incorporating a comprehensive maritime shipping module (WITCH-Shipping). This innovation enables a substantially more accurate representation of international shipping within integrated assessment frameworks, addressing persistent deficiencies in prior global analyses of bunker fuels, inter-fuel competition, and cross-sectoral linkages. Second, it provides the first quantitative evaluation of the Net Zero Framework proposed at MEPC 83, offering a rigorous techno-economic and system-wide assessment of its effectiveness within a fully integrated global mitigation pathway.

5.2. METHODS

This study uses the WITCH v6.0 model, a widely applied integrated assessment model featured in recent IPCC Assessment Reports [1, 212]. The model combines an intertemporal macroeconomic optimisation framework with a detailed representation of energy technologies. The model identifies cost-effective combinations of mitigation and adaptation options while accounting for regional welfare, externalities, and free-riding behaviour. Regional utility is maximised within a social-planning setup and reflects choices regarding fossil-fuel use, abatement, and investment. The model runs from 2005 to 2100 in five-year steps and includes seventeen world regions that differ in economic structure, resource endowments, and demographic trends. Its main strength lies in linking macroeconomic dynamics to detailed energy technology pathways, thereby capturing sectoral interactions in a consistent manner. A new maritime shipping module is incorporated into WITCH for this study. This WITCH-shipping model links vessel classes and size groups with alternative fuel technologies, investment requirements, and policy constraints. It enables the representation of shipping activity, technology uptake, and fuel use within the broader energy, economy, and climate system, and allows maritime emissions to respond consistently to global and sector-specific policies. Technical documentation for the WITCH framework is publicly available through the IAMC model archive [134, 135].

5.2.1. FUEL TECHNOLOGIES

Oil based fuels remain dominant in maritime transport because they benefit from mature infrastructure and relatively low costs, yet their use leads to high greenhouse gas emissions and other pollutants. Biofuels can reduce emissions and are produced mainly from lignocellulosic residues and agricultural byproducts, although their large-scale use is constrained by feedstock availability and competition with land and food production. Liquefied natural gas reduces sulfur oxides and particulate matter but faces uncertainty in well-to-wake performance due to methane slip. Hydrogen and hydrogen-based fuels, including ammonia, methanol, and synthetic diesel, offer the largest long-term potential for deep decarbonization. Their environmental performance depends on production routes. Hydrogen may be produced from natural gas with or without carbon capture, or from renewable electricity through electrolysis [18, 213]. These pathways form the basis for producing ammonia through the Haber-Bosch process and for generating methanol and e-diesel by combining hydrogen with captured carbon dioxide [214–216]. Hydrogen can also be used directly in fuel cell vessels, although its low volumetric energy density and storage requirements make it more suitable for short-sea and inland applications.

These fuel pathways are represented in the model as technology chains that convert primary energy into marine fuels by combining electricity, biomass, and fossil feedstocks. All fuels are evaluated on a well-to-wake basis to ensure lifecycle emissions and energy use are comparable across options. Oil, biofuels, and natural gas supply follow their standard representations in WITCH [134, 217], while the production of hydrogen, ammonia, methanol, and e-diesel is added in this study. Hydrogen production is modeled via steam methane reforming with or without carbon capture, and via electrolysis, with electrolysis costs declining over time due to learning-by-doing. Ammonia, methanol, and e-diesel synthesis require hydrogen and, in the case of carbon-based fuels, a source of captured carbon.

The installed capacity for each technology j in region n and period t evolves according to:

$$K_{j,t+1,n} = K_{j,t,n}(1-\delta_j)^{\Delta t} + \Delta t \frac{I_{j,t,n}}{SC_{j,t,n}}, \tag{5.1}$$

$$\delta_j = 1 - \exp\left(\frac{1}{-\mathrm{lifetime}_j + \frac{0.01}{2}\mathrm{lifetime}_j^2}\right), \tag{5.2}$$

This formulation applies the standard neoclassical capital-stock rule with exponential retirement of assets [218]; where $K_{j,t,n}$ denotes installed capacity, δ_j is the effective annual depreciation rate, Δt is the five-year time step, $I_{j,t,n}$ is the investment decision variable, and $SC_{j,t,n}$ is the specific installation cost per unit of capacity. OPEX is applied in each time step as a fixed share of CAPEX. Table 5.2 lists key parameters. Global average values are used for process parameters, while input energy costs vary by region and scenario, depending on the resource endowment. More detailed formulations of the equations are provided in fig. B.3 and table B.6 in the Appendix. Additional details on fuel production pathways and the internal connectivity between vessels and fuels are presented in figs. B.4 and B.5.

Table 5.2.: Key parameters for each process step.

Process	η_j	$SC_{t0,j}[\$/W]$	OPEX	Hours/yr	Input C [$\mathrm{kg_C}$/kWh]	Ref.
PEM electrolyzer	60%	1.20	2%	5000	–	[219–221]
SOEC electrolyzer	70%	2.20	2%	5000	–	[219–221]
Fischer–Tropsch	71%	1.76	1.5%	7920	0.073	[222, 223]
Haber–Bosch	87%	2.01	4%	7920	–	[224, 225]
Methanol synthesis	83%	1.64	1.5%	7920	0.068	[226, 227]

1: OPEX is expressed as a fraction of CAPEX per year.

Each technology chain is characterized by its investment needs, operating costs, and conversion efficiencies, and evolves through investment decisions that reflect relative costs and policy incentives. Electrolyzer investment costs decline through learning-by-doing, represented by standard experience curves. The cost of a technology decreases by a constant fraction with each doubling of cumulative installed capacity or cumulative production activity [228]. Thus, investment costs evolve as a function of cumulative global capacity according to the following equations.

$$W_{j,t}^{\mathrm{cum}} = W_{j,t-1}^{\mathrm{cum}} + \mathrm{tlen}_t \sum_n \frac{I_{j,t,n}}{SC_{j,t,n}}, \tag{5.3}$$

$$SC_{j,t,n} = \max\left[SC_{\mathrm{min}},\, SC_{j,t_0,n}\left(\frac{W_{j,t}^{\mathrm{cum}}}{W_{j,t_0}^{\mathrm{cum}}}\right)^{-\gamma}\right], \tag{5.4}$$

where γ is the learning coefficient and SC_{min} is the lower bound on cost. The progress ratio $(pr) = 2^{-\gamma}$ and the learning rate $(lr) = 1 - pr$ define the cost decline. Learning rates of 14% for proton-exchange-membrane (PEM) and 17% for solid-oxide (SOEC) electrolyzers are implemented, consistent with recent empirical evidence [229].

5.2.2. ADDITIONAL COST OF VESSEL AND ENGINE MODIFICATIONS

Investment costs for ships are estimated using historical data from Clarkson shipbuilding contracts, expressed per unit of carrying capacity [230]. Additional capital costs for vessels that use alternative fuels are taken from the Total Cost of Ownership framework developed by Zero Carbon Shipping, which provides consistent estimates of acquisition and operating costs for different fuel and propulsion systems [231].

Using conventional oil-fueled engines as the reference case, we compute average capital cost multipliers for ships powered by ammonia, methanol, natural gas, and for vessels that use hydrogen through fuel cell propulsion. These higher costs reflect the need for modified engines, specialised fuel storage systems, and enhanced safety requirements. Multipliers are derived across tankers, bulk carriers, and containerships to ensure comparability (Table 5.3). All vessels are assumed to operate for 25 years, with depreciation applied at each model time step. Fleet capacity expands in line with projected trade and shipping demand so that transport supply matches cargo movements.

Table 5.3.: CAPEX multipliers for alternative-fuel vessels.

Vessel type	ICDF	ICDG	ICA	ICM	ICG	FC
Tanker	1.00	1.00	1.11	1.08	1.13	2.57
Bulk carrier	1.00	1.00	1.14	1.09	1.17	2.94
Containership	1.00	1.00	1.19	1.14	1.25	4.11

Abbreviations: ICDF = internal combustion diesel (oil-based fuels); ICDG = internal combustion using green drop-in fuels such as biofuels or e-diesel; ICA = internal combustion ammonia; ICM = internal combustion methanol; ICG = internal combustion natural gas; FC = hydrogen fuel cell.
Source: Calculations based on the TCO tool developed by Zero Carbon Shipping [231].

5.2.3. INPUT ENERGY REQUIREMENT

Future energy use in international shipping is generated through two connected modelling steps. First, macroeconomic growth and carbon price signals from the WITCH model are translated into projections of maritime transport activity. This follows a gravity based approach that estimates bilateral trade volumes for three cargo groups: energy commodities, major bulks, and containerised goods. Trade flows depend on regional production and consumption, income growth, relative fuel prices, and distances between trading partners, and are expressed in transported mass rather than economic value. Estimated flows in tonnes are converted to ton miles using representative sea routes, with major geographic chokepoints and vessel size restrictions included to maintain realistic routing. The full methodological details for this component are provided in previous studies that developed the trade module [232]. Because this trade module operates within the WITCH framework, the same socioeconomic and policy assumptions shape both land based energy demand and maritime transport dynamics.

The second step converts transport activity into fuel use. Bilateral flows are allocated across tankers, bulk carriers, and containerships, each divided into size classes based on recent AIS observations of route length and vessel deployment [144]. This allocation reproduces the way the existing fleet is distributed across long haul and regional trades. For each vessel and size group, average fuel intensity from the IMO Fourth

GHG Study is applied and combined with standard emission factors. Vessel productivity, expressed as ton miles per unit of capacity, is taken from the same dataset. More detailed descriptions of this mapping and fuel intensity estimation can also be found in earlier work [230].

Through this structure, shipping activity and fuel consumption respond directly to changes in GDP, trade patterns, and fuel prices generated by each scenario. This coupling ensures that shipping emissions remain consistent with the broader energy, economy, and climate dynamics represented in the WITCH model.

5.2.4. SCENARIO ASSUMPTIONS

Note: Scenarios in this chapter differ from those used in Chapter 3. The reason is threefold. First, Chapter 3 focuses on shipping demand, whereas this chapter examines the supply of marine fuels. These perspectives involve different mechanisms and therefore require different scenario designs to observe, test, and interpret the relevant dynamics. Second, the scenarios reflect advances in climate-policy modeling since the earlier analysis. In particular, the mitigation framework is updated from a carbon-tax–based approach to a carbon-budget formulation, which better aligns with current practice in the literature. Third, while the EU early-mitigation scenario yielded informative insights on the demand side, it adds limited value for fuel supply analysis. Early movers mainly shift faster, but once other regions adopt similar policies, they largely catch up in fuel transitions, leading to similar long-run supply outcomes.

All scenarios follow the SSP2 socioeconomic pathway and apply a global carbon budget consistent with limiting end-of-century warming to 1.5°C. The scenarios differ in global climate ambition, sector-specific regulation, and the availability of ammonia as a marine fuel. Biofuel use is constrained by regional supply limits taken from GLOBIOM [217]. Direct air capture and bioenergy with carbon capture and storage are available under the standard assumptions used in the WITCH documentation [134]. Ship engine efficiency improves exogenously by 0.4% per year, which corresponds to 2% per model time step.

Six scenarios are implemented, each defined by the strength of the global mitigation signal, the presence or absence of sector-specific measures, and the availability of ammonia. All scenarios follow the SSP2 socioeconomic pathway. The 1.5 °C cases are derived by imposing a fixed global carbon budget that ensures end-of-century warming remains below 1.5 °C, with the associated economy-wide carbon price emerging endogenously. Sector-specific policies follow the structure proposed at MEPC 83. The Net-Zero Framework (NZF) combines a global well-to-wake fuel-intensity standard with a pricing mechanism. The remedial prices follow the indicative Tier values discussed at MEPC 83: 100 $ per tonne of CO_2 for Tier 1 non-compliance and 380 $ per tonne of CO_2 for Tier 2. In scenarios where the NZF is applied, these prices are charged on fuel use that exceeds the intensity limits specified for each compliance period. The scenario without ammonia removes all ammonia-based fuels from the technology portfolio of shipping to evaluate the implications of excluding a major zero-carbon option due to safety and operational concerns. The IMO-aligned scenario imposes sector-specific emission caps consistent with the 2023 IMO GHG Strategy: a 70% reduction by 2040 and full well-to-wake decarbonization by 2050. These constraints are applied directly to international shipping emissions within the model. The complete configuration of the six scenarios is summarized in Table 3.4. And, more supplementary model outputs are presented in appendix E.

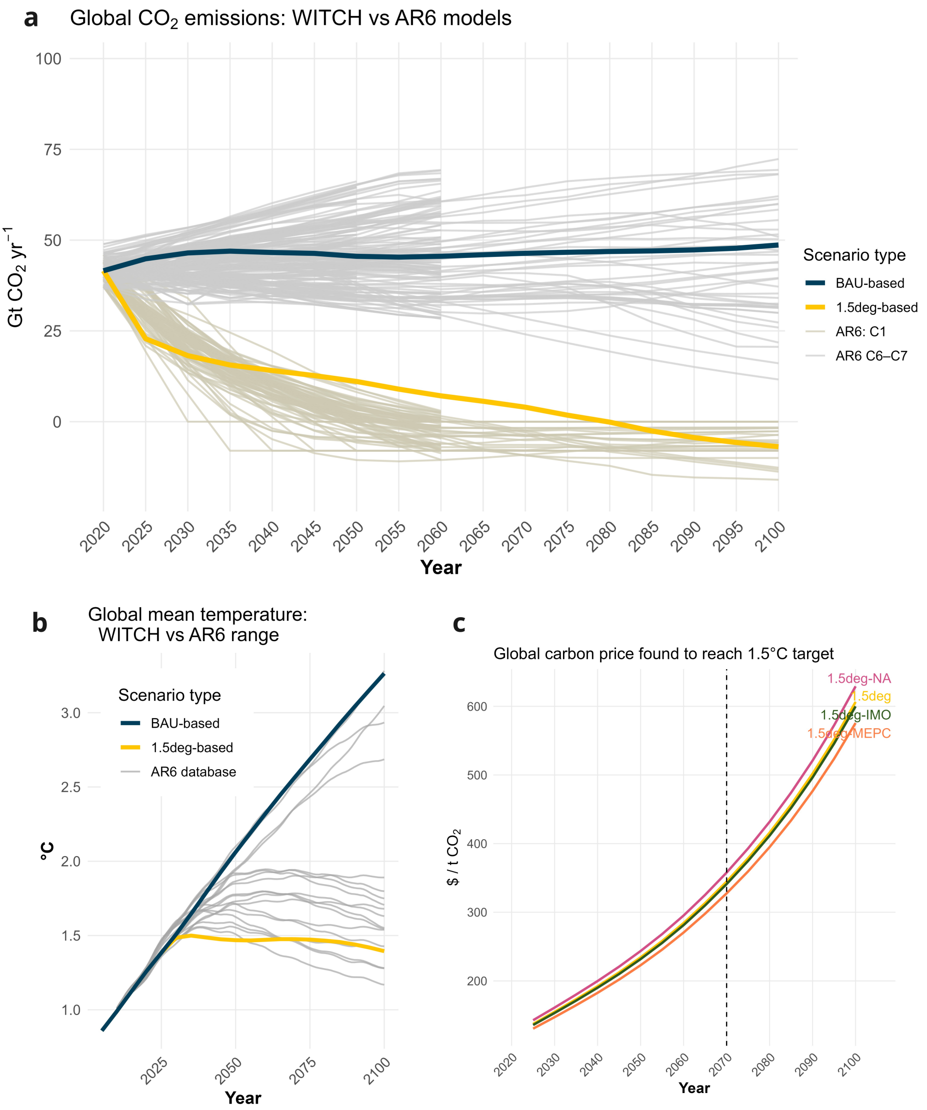

Figure 5.1.: **WITCH–Shipping global climate outcomes benchmarked against AR6 pathways.** **a**, Global CO_2 emissions across scenarios compared with AR6 ranges (grey). **b**, Global mean temperature change relative to pre-industrial levels, showing consistency with AR6 median behaviour under both *baseline* and *1.5°C*-based pathways. **c**, Endogenous global carbon price trajectories required to satisfy the 1.5 °C carbon budget, with higher prices in the *1.5°C-NA* case and lower prices under *1.5°C-IMO* and *1.5°C-MEPC* due to sector-specific measures.

Ensuring that the scenario design is globally consistent requires that the WITCH-Shipping outcomes fall within established AR6 ranges for emissions, warming, and carbon prices. Global CO_2 trajectories in *baseline* and the *1.5°C*-based pathways lie well inside the AR6 envelopes (Fig. 5.1a). In *baseline*, emissions remain close to 50 $GtCO_2\,yr^{-1}$ throughout the century, consistent with AR6 C6–C7 behaviour, while all *1.5°C*-aligned cases follow the C1 range, declining rapidly and falling below zero after the 2070s as removals scale. Adding sector-specific shipping policies does not meaningfully distort the global system response as the carbon target is set.

Global mean temperature outcomes track the AR6 distributions closely (Fig. 5.1b). The imposed 1.5 °C carbon budget produces end-century warming near the AR6 median, confirming the internal consistency of the coupled climate–economy module.

Given the fixed carbon budget, the model computes the economy-wide carbon price needed to maintain compatibility with 1.5 °C (Fig. 5.1c). The *1.5°C-NA* case yields higher global carbon prices because delayed shipping decarbonisation forces stronger mitigation elsewhere. By contrast, *1.5°C-IMO* and, especially, *1.5°C-MEPC* require lower global carbon prices, as their sector-specific measures directly reduce shipping emissions and ease pressure on the rest of the economy.

5.2.5. MODEL CALIBRATION AND VALIDATION

The maritime module is calibrated to observed conditions in the base year. Fuel consumption, fuel intensities, and vessel productivity follow the IMO Fourth GHG report, and 2020 emissions match the IMO estimation. The initial fuel mix reflects the dominance of oil based fuels with a small share of liquefied natural gas, consistent with IMO and UNCTAD data [4, 52]. Fuel-mix validation is performed in the no-policy *baseline* scenario. Existing modelling studies consistently show that, without climate intervention, oil remains dominant in international shipping through 2050 and LNG is the only alternative fuel that expands at meaningful scale. The model reproduces this pattern, yielding an LNG share of roughly 20% in 2050, which falls comfortably within published ranges from sectoral and integrated assessment studies. Validation plots are provided in the Supplementary Information.

5.3. RESULTS

5.3.1. EMISSIONS PATHWAYS FOR INTERNATIONAL SHIPPING

All decarbonization scenarios implemented in the WITCH-Shipping model reduce global emissions in line with 1.5 °C-consistent pathways. International shipping exhibits a distinct decarbonization pattern due to fuel

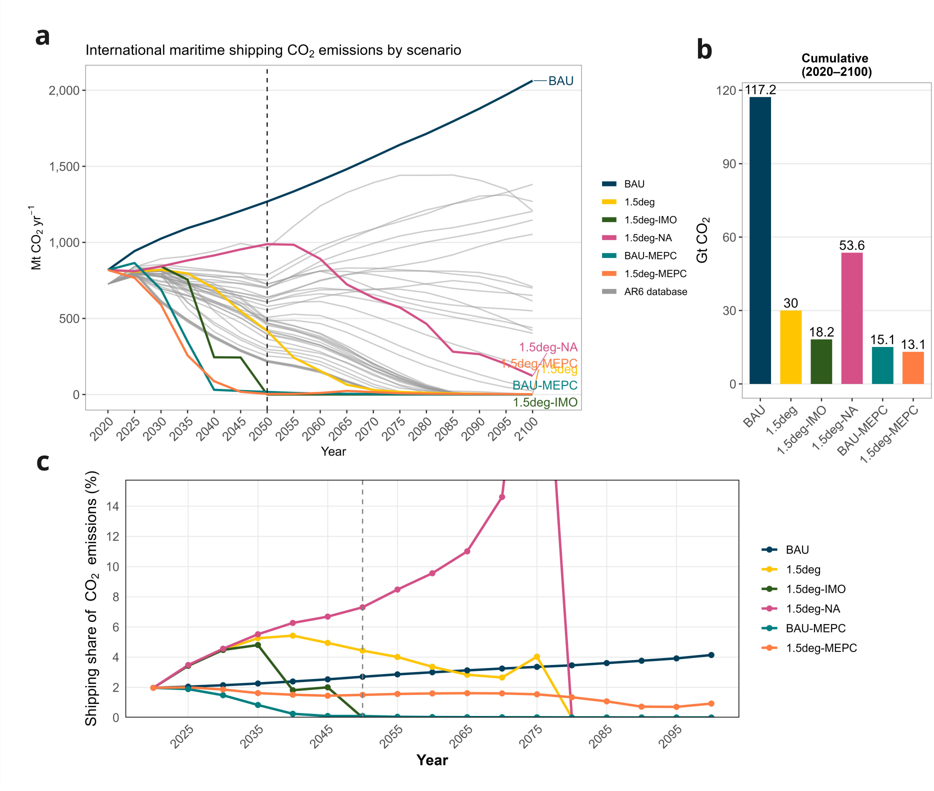

Figure 5.2.: **International shipping** CO_2 **emissions and global share across scenarios.** **a**, Annual CO_2 emissions from international maritime shipping across six scenarios, with AR6 (6th Assessment Report by IPCC [233] pathways shown in grey for comparison. **b**, Cumulative shipping emissions over 2020–2100. **c**, Shipping's share of global CO_2 emissions, illustrating how sectoral mitigation evolves relative to economy-wide decarbonisation.

constraints, technology availability, and policy timing. Figure 5.2 summarises how sectoral CO_2 emissions evolve across six scenarios.

Under *baseline*, emissions rise steadily and exceed 2 $GtCO_2\,yr^{-1}$ by 2100 due to continued reliance on fossil fuels and the absence of new policy. In the *1.5°C* scenario, emissions decline early but do not approach zero before the 2070s. The *1.5°C-IMO* scenario reduces emissions by 70% by 2040 and reaches zero by 2050 in line with imposed IMO targets. Excluding ammonia from the *1.5°C-NA* scenario substantially slows decarbonisation, and emissions begin to decline only after the mid-2050s. The *baseline-MEPC* and *1.5°C-MEPC* scenarios produce large reductions and reach near-zero emissions before 2050 without imposing hard constraints on the model. Compared with the AR6 database, *baseline* grows more rapidly than most reported pathways, whereas all mitigation scenarios decline more rapidly. The grey AR6 trajectories lie mainly above the *1.5°C* pathways, and almost none achieve full decarbonisation by 2050. This difference reflects the explicit modelling of shipping activity, fuel competition, IMO policy timing, and fleet turnover in WITCH-Shipping, which is largely absent in the AR6 scenarios (Fig. 1a).

Cumulative emissions over 2020–2100 vary widely across scenarios (Fig. 1b). *baseline* accumulates roughly 117 $GtCO_2$. The *1.5°C* and *1.5°C-IMO* pathways reduce this total to about 30 and 18.2 $GtCO_2$, respectively, roughly one-quarter of *baseline*. The *1.5°C-NA* scenario results in much higher cumulative emissions, highlighting the central role of ammonia as a scalable marine fuel. The MEPC-based pathways achieve the largest reductions, with *baseline-MEPC* and *1.5°C-MEPC* reaching the lowest cumulative totals. The avoided emissions between the most and least ambitious cases correspond to roughly 25%–35% of the remaining global carbon budget for a two-thirds chance of limiting warming to 1.5 °C with low or no overshoot [1, 94].

Shipping's share of global CO_2 offers an additional perspective on its role in the wider mitigation effort, indicating how rapidly the sector decarbonises relative to the rest of the economy (Fig. 1c). In *baseline*, shipping's share of global CO_2 rises steadily and exceeds 4% by 2100 as other sectors decarbonise more rapidly. In the *1.5°C* and *1.5°C-IMO* scenarios, the share peaks around 2035 at roughly 5% and then declines as emissions fall later in the century. The *1.5°C-NA* scenario shows a sharp spike because other sectors mitigate quickly, while shipping lacks access to its most cost-effective fuel option. In contrast, *baseline-MEPC* and *1.5°C-MEPC* reduce shipping's share to near zero before 2050.

5.3.2. TRANSITION OF THE MARINE FUEL MIX

Technological transitions in shipping drive the emissions pathways discussed above. Figure 5.3 shows how the global marine fuel mix evolves across scenarios over the century. Fuel availability and cost play a central role in shaping these transitions, as the competitiveness of ammonia, biofuels, e-diesel, methanol, LNG, and oil-based fuels determines both the timing and scale of decarbonisation.

In (Fig. 2a), *baseline* remains dominated by oil across the century, with only a slow and limited shift towards LNG. In the *1.5°C* scenario, ammonia gradually replaces oil after mid-century as costs fall and production expands. The *1.5°C-IMO* scenario transitions even faster, achieving near-total ammonia use by 2050, complemented by biofuels that complete the final stages of decarbonisation. Without ammonia, the *1.5°C-NA* scenario fragments into methanol, biofuels, LNG, and small amounts of direct hydrogen for short-haul segments. Decarbonisation is delayed until after 2060, and the system relies increasingly on biofuels and methanol

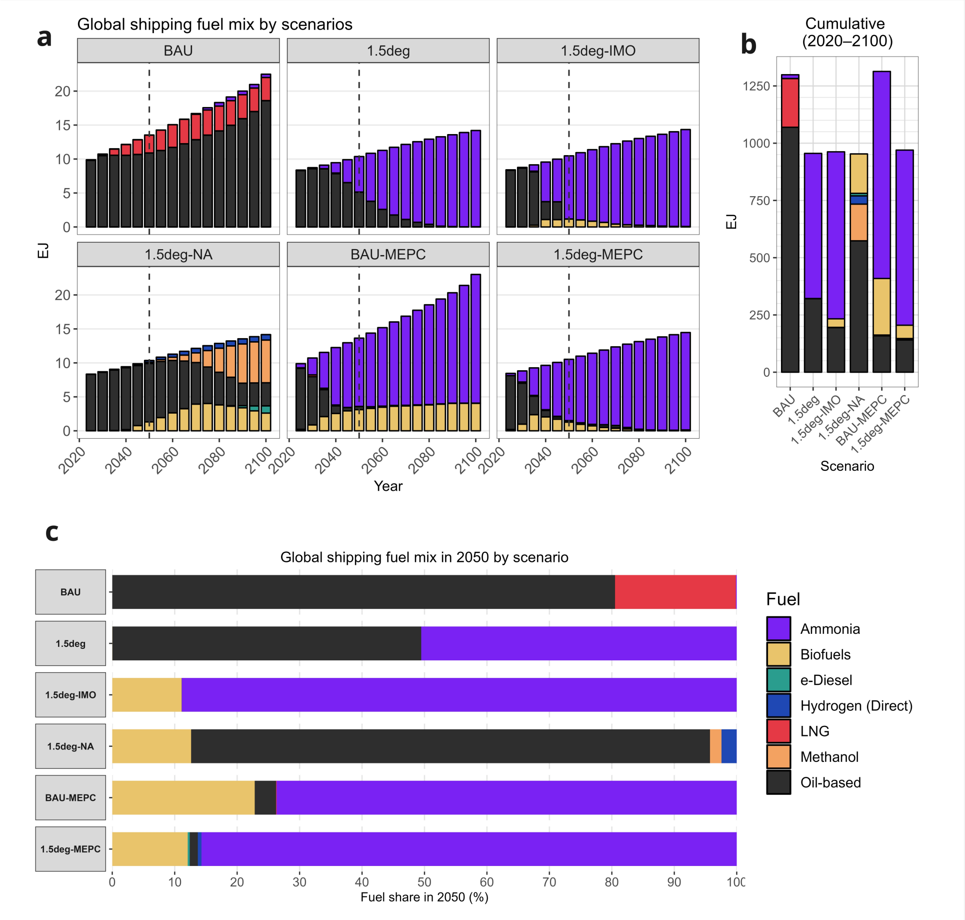

Figure 5.3.: **Transition of the global marine fuel mix across scenarios. a**, Annual global shipping fuel use by scenario, showing the timing and scale of transitions from oil-based fuels toward ammonia, biofuels, methanol, e-diesel, LNG, and direct hydrogen. **b**, Cumulative fuel use over 2020–2100, highlighting large differences in total energy demand and the dominance of ammonia in ambitious pathways. **c**, Fuel mix in 2050 across scenarios, illustrating the contrasting roles of marine fuels in mid-century decarbonisation strategies.

as scaling options, along with marginal e-diesel as a complementary fuel. By 2050, fuel use in this scenario remains almost entirely oil-based, since other sectors draw heavily on natural gas and low-carbon feedstocks while shipping lacks access to its most cost-effective marine fuel. Both *baseline-MEPC* and *1.5°C-MEPC* combine ammonia and biofuels with rapid transitions. *baseline-MEPC* reaches full decarbonisation earlier, while *1.5°C-MEPC* retains marginal oil use due to cross-sector competition for clean energy carriers. This confirms the effectiveness of the net-zero framework proposed under MEPC 83, provided it is implemented promptly. Across all ambitious pathways, ammonia dominates because it does not require carbon inputs for production and remains cost-competitive at scale.

Figure 2b shows cumulative fuel use over 2020–2100. *baseline*-based pathways have the highest totals because endogenous activity levels are larger under higher economic growth and lower fuel prices, which increase shipping demand. A substantial part of this difference reflects the much higher trade in oil and petroleum products in *baseline*-based scenarios compared with the *1.5°C* pathways. Detailed shipping activity results are provided in the Supplementary Information. Both *1.5°C* and *1.5°C-IMO* reduce cumulative fossil fuel use by more than 800 EJ, which is almost four times the global oil consumption in 2020 [234]. Ammonia provides the majority of cumulative energy in all ambitious scenarios, followed by biofuels, particularly in *baseline-MEPC*. These cumulative patterns are consistent with the emissions trajectories shown in Fig. 1.

Figure 2c highlights the fuel mix in 2050, a year central to discussions on what decarbonised shipping may look like. In the decarbonisation pathways, most scenarios display a dominance of ammonia at mid-century, completed by biofuels and small contributions from e-diesel and direct hydrogen. A notable observation is that the *1.5°C-NA* pathway uses more oil in 2050 than *baseline*, reflecting the combination of strong cross-sector competition for clean fuels and the exclusion of ammonia from the marine fuel portfolio. These fuel-mix differences help explain the divergent emissions outcomes presented in Fig. 1.

5.3.3. FUEL COSTS AND INVESTMENTS

Fuel choices emerge from the investment landscape that enables them. Decarbonising international shipping reshapes demand for hydrogen, ammonia synthesis, and renewable power, linking sectoral transition to upstream technology scale-up. Figure 5.4 illustrates how shipping scenarios affect shipping fuel prices, hydrogen infrastructure spending, and renewable-energy investment.

Average fuel prices[1] in shipping evolve in line with upstream fuel-market dynamics (Fig. 3a). Prices start at roughly 0.04 $ kWh^{-1} and rise in the near and medium term across all decarbonisation pathways as clean-fuel production scales. Under the global 1.5 °C policy signal, prices converge after mid-century, and by 2100 fall slightly below *baseline*, indicating that early investment in hydrogen-based fuels yields long-term cost benefits. The IMO-forcing and MEPC-aligned pathways show a sim-

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[1] This is estimated ex-poste considering CAPEX, OPEX, lifetime, efficiencies, and adoption rates endogenously within the model.

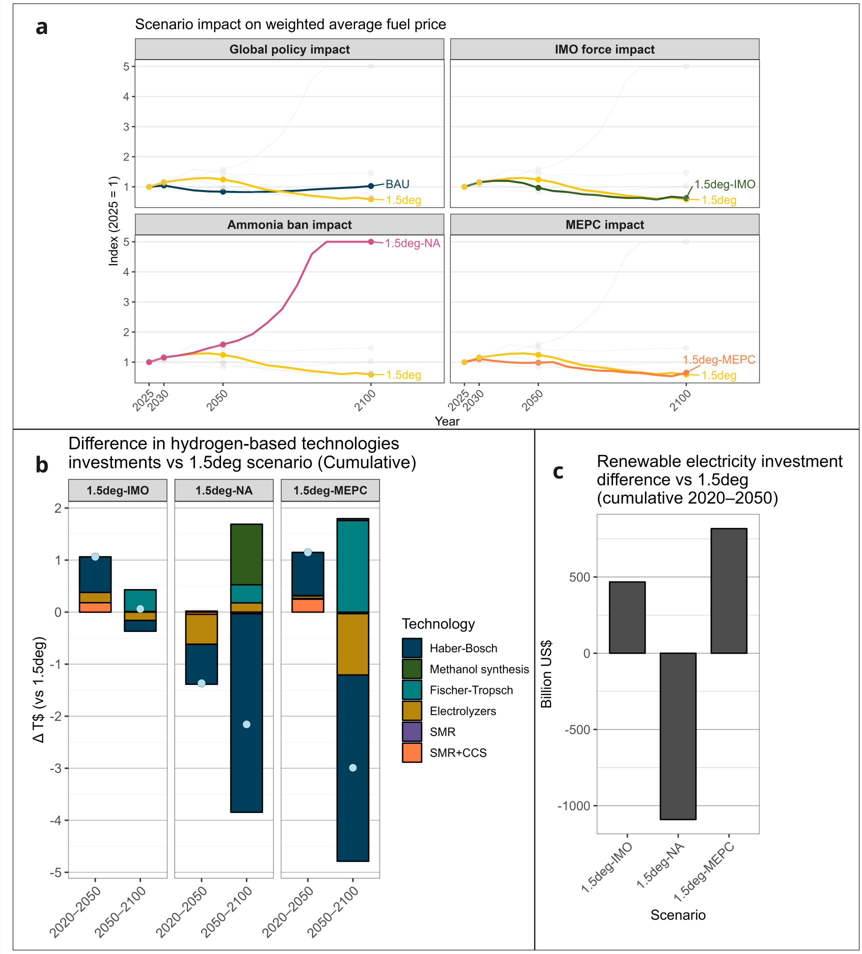

Figure 5.4.: **System-wide economic and investment implications of shipping decarbonisation.** **a**, Scenario impacts on the weighted-average fuel price used in international shipping, indexed to 2025. **b**, Difference in cumulative hydrogen-based fuel-supply infrastructure investment relative to the 1.5 °C scenario over 2020–2050 and 2050–2100, including electrolyser, Haber–Bosch ammonia synthesis, methanol and Fischer–Tropsch conversion, and SMR and SMR+CCS systems. **c**, Difference in cumulative renewable electricity investment relative to the 1.5 °C scenario over 2020–2050. Renewables include onshore and offshore wind, solar PV and CSP, renewable biomass, hydropower, and geothermal technologies.

ilar pattern but with an earlier transition: stronger constraints or incentives for clean-fuel deployment bring average fuel prices below *baseline* already by 2050, after which trajectories converge. The *1.5°C-NA* case produces the strongest divergence. Fuel prices rise gradually at first, then surge because ammonia is excluded from the marine fuel mix and the carbon price required to meet the 1.5,° C constraint makes oil-based fuels increasingly costly. The resulting fuel price reaches more than five times the reference level (capped to preserve figure readability). Across all pathways, fuel availability exerts a larger influence on shipping fuel costs than policy design alone. The evolution of fuel prices reflects the scale and timing of fuel deployment, making the upstream investment profile the main driver of long-run marine energy costs.

Cumulative investment in hydrogen-based fuel supply differs markedly across the mitigated scenarios. Imposing the IMO targets (*1.5°C-IMO*) requires approximately 1 T$ of additional spending by mid-century relative to *1.5°C*, that of hydrogen production split almost evenly between expanded green (electrolysis) and blue (SMR+CCS) hydrogen production. This additional spending is comparable to one year of current global investment in fossil-fuel supply [234]. In contrast, removing ammonia from the technology portfolio (*1.5°C-NA*) substantially lowers investment needs by both 2050 (around 1.5 T$ less) and 2100 (morethan 2 T$ less), driven by strongly reduced Haber–Bosch deployment and a shift toward methanol and Fischer–Tropsch synthesis. The *1.5°C-MEPC* pathway prioritises early build-out, more than 1 T$ above *1.5°C* by 2050, primarily in blue hydrogen and ammonia synthesis. These early investments reduce long-term costs; during 2050–2100, total investment in *1.5°C-MEPC* falls well below the other cases as mature supply chains reduce electrolyser and ammonia-plant spending.

Renewable electricity investment also responds directly to the hydrogen requirements implied by the shipping scenario (Fig. 3c). Relative to the *1.5°C* scenario, the *1.5°C-IMO* pathway requires moderately higher renewable capacity additions, while the *1.5°C-NA* case requires almost 1 T$ less investment due to reduced hydrogen production. In contrast, the *1.5°C-MEPC* pathway induces more than 750 B$ additional renewable investment by 2050, driven by accelerated green ammonia and e-fuel production. These values fall well within ranges reported for global renewable expansion in IEA, ETC, and AR6 mitigation pathways, underscoring that the system-level adjustments required by shipping remain a modest fraction of global energy investment needs.

Fuel prices, hydrogen-supply infrastructure, and renewable-energy investments together show that shipping decarbonisation produces system-wide economic adjustments. Because these shifts extend well beyond the maritime sector, the next section explores how shipping pathways interact with the broader energy system.

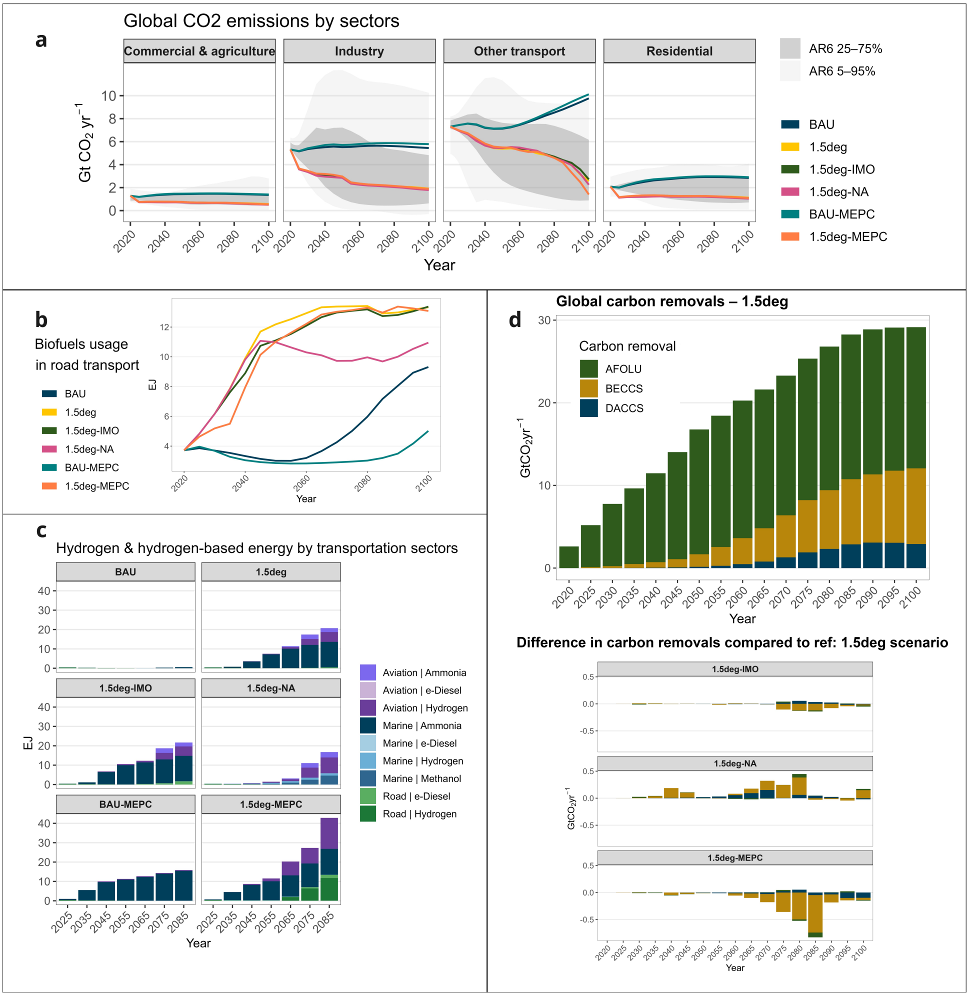

Figure 5.5.: **System-wide implications of shipping decarbonisation.** **a**, Global CO_2 emissions by sector across scenarios, with AR6 25–75 % and 5–95 % ranges shown in grey. **b**, Biofuel consumption in road transport, highlighting cross-sector biomass competition in *baseline*-based and ammonia-ban pathways. **c**, Hydrogen and hydrogen-derived energy use across marine, aviation and road transport. **d**, Global carbon removals in the reference 1.5 °C pathway (AFOLU, BECCS, DACCS; top) and scenario differences relative to that pathway (bottom). AFOLU refers to land-based carbon removals from agriculture, forestry and other land use; BECCS to bioenergy with carbon capture and storage; and DACCS to direct air capture with carbon capture and storage.

5.3.4. BEYOND SHIPPING INTERACTIONS

Marine fuel choices interact with the broader energy system, influencing fuel allocation, upstream hydrogen production, biofuel availability, and the scale of carbon removals required to meet long-term climate goals. Figure 5.5 summarises these system-wide effects across sectors.

Emissions in commercial/agriculture and residential sectors remain largely insensitive to shipping-sector variation as their supply chain is mainly different (Fig. 5.5a). Small deviations, however, arise in industry and other transport: in *baseline*-based scenarios, the shipping taxation attracts biomass feedstock and biofuels toward international shipping, leaving slightly lower availability for other transport modes and industry. All trajectories remain well within the AR6 database ranges, supporting the internal validity of the model. This cross-sector fuel competition is also visible in road-transport biofuel use (Fig. 5.5b). *baseline* and *baseline-MEPC* exhibit the largest divergence, reflecting the pull of biofuels toward shipping. In the *1.5°C-NA* pathway, banning ammonia induces higher biofuel reliance in shipping, correspondingly reducing biofuel availability for road transport.

Hydrogen and hydrogen-derived fuels show stronger cross-sector coupling (Fig. 5.5c). When ammonia is available (*1.5°C*, *1.5°C-IMO*, *1.5°C-MEPC*), international shipping absorbs most hydrogen in the form of ammonia. The *1.5°C-MEPC* case shows earlier and larger scaling of ammonia production, lowering upstream hydrogen costs and enabling spillovers into aviation and road by 2100 through hydrogen and its derivatives use. Under the ammonia-ban scenario, aviation becomes the dominant hydrogen user from mid-century onward, with shipping relying mainly on methanol and marginal e-diesel until late-century. In *baseline-MEPC*, hydrogen flows almost exclusively to shipping, with negligible uptake in other modes. Across all cases, the interaction between fuel competition and the timing of clean-fuel investment determines the distribution of hydrogen across transport sectors.

Carbon-removal responses mirror these fuel-system shifts (Fig. 5.5d). The upper panel shows annual AFOLU, BECCS and DACCS removals in the reference *1.5°C* scenario. The lower panel presents deviations from that baseline. The *1.5°C-IMO* pathway requires slightly lower removals later on. The *1.5°C-NA* pathway requires more carbon removal overall because shipping remains oil-dependent, leaving higher residual emissions elsewhere in the economy. In addition, removing ammonia forces a shift to synthetic methanol and e-diesel, which require DAC–CCU for their carbon feedstock; this expands DAC capacity for fuel production and indirectly raises its availability for long-term atmospheric removal. In contrast, the *1.5°C-MEPC* case requires less removal overall as earlier fuel switching in shipping reduces economy-wide residual emissions.

Taken together, these results show that the maritime sector's fuel choices propagate across the wider energy system, influencing biofuel availability for other sectors, hydrogen allocation, and carbon-removal requirements. Ammonia availability emerges as the key determinant of these upstream and downstream system responses.

5.3.5. SENSITIVITY ANALYSIS

ELECTROLYZER LEARNING RATE ASSUMPTIONS

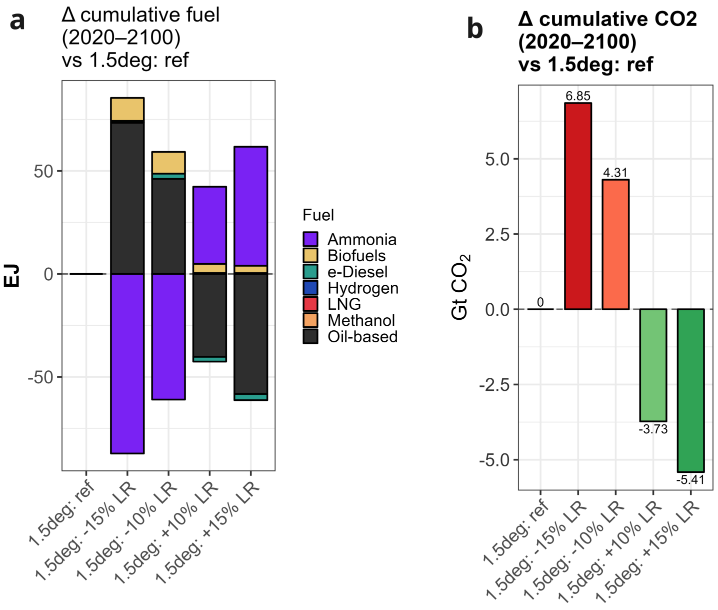

Figure 5.6.: **Sensitivity of fuel use, emissions, and ammonia deployment to electrolyser learning rates.** **a**, Change in cumulative fuel use over 2020–2100 relative to the 1.5deg reference scenario for learning-rate variations of ±10% and ±15%, showing substitution between ammonia and oil-based fuels. **b**, Corresponding change in cumulative CO_2 emissions, with slower learning (higher costs) increasing emissions and faster learning reducing them.

To assess the robustness of the model, we vary electrolyser learning rates by ±10% and ±15% relative to the standard 1.5 °C scenario. These variations directly affect the cost of hydrogen-derived fuels, particularly ammonia. The 1.5 °C scenario is used as the reference because hydrogen-based marine fuels are deployed at scale in that pathway, unlike in *baseline*, and because no additional constraints or structural differences introduce bias in the comparison (Figure 5.6).

A faster learning rate reduces electrolysis costs and increases ammonia use, displacing oil and biofuels, whereas a slower learning rate has the opposite effect (Fig. 5a). The magnitude of the response is asymmetric: the *1.5°C:*−15% *LR* case shifts roughly 90 EJ of energy relative to the reference, whereas the *1.5°C:*+15% *LR* case shifts about 60 EJ. These changes reflect the strong cost sensitivity of ammonia, which remains the dominant low-carbon fuel in all ambitious pathways.

Cumulative emissions change in line with these fuel adjustments (Fig. 5b). Faster learning lowers century-wide emissions by 5.4 $GtCO_2$, while slower learning raises emissions by 6.8 $GtCO_2$ relative to the reference. These differences are modest compared with the full-scenario variations in Fig. 1 but remain material over the century, driven entirely by shifts between ammonia and fossil or biomass-derived fuels.

Overall, electrolyser learning rates affect the scale and timing of ammonia uptake but do not alter the qualitative structure of the decarbonisation pathway.

MEPC-TIMING TEST

Given the central role of the MEPC-aligned levy in the main results, we assess how its effectiveness depends on the timing of implementation. This sensitivity test is particularly relevant because the proposed framework has already experienced an initial delay, raising questions about the consequences of further postponement. We therefore compare levy start dates in 2025, 2030, and 2035 against the 1.5 °C carbon budget reference scenario (Figure 5.7).

Early implementation induces a rapid shift away from oil-based fuels, adding nearly 200 EJ of cumulative clean-fuel use over the century, driven primarily by ammonia and biofuels. Delaying the levy by just five years reduces this substitution by roughly half, to about 100 EJ, while a ten-year delay lowers it further to around 75 EJ (Fig. 5.7a). The emissions response is similarly nonlinear. A 2025 start cuts cumulative shipping emissions by approximately 17 $GtCO_2$ relative to the reference case, whereas delaying to 2030 halves this benefit, and a 2035 start reduces it to about 5.8 $GtCO_2$. Notably, the emissions gap between a 2025 and 2030 start alone is comparable to nearly a decade of current shipping emissions, indicating that early years dominate long-term mitigation outcomes (Fig. 5.7b).

To place these physical impacts in an economic context, we examine cumulative policy cost, defined here as the discounted global GDP loss relative to the no-policy baseline, reported as percentage differences with respect to the 1.5,° C reference scenario (Fig. 5.7c). When implemented from 2025, the MEPC-aligned levy substantially lowers total policy costs by accelerating clean-fuel investment in shipping and generating positive spillovers to the wider energy system, reducing cumulative policy costs by about 3%. Delaying implementation to 2030 eliminates most of this benefit, shifting the effect to a slight increase of roughly 0.2% over the century. A further delay to 2035 raises costs to around

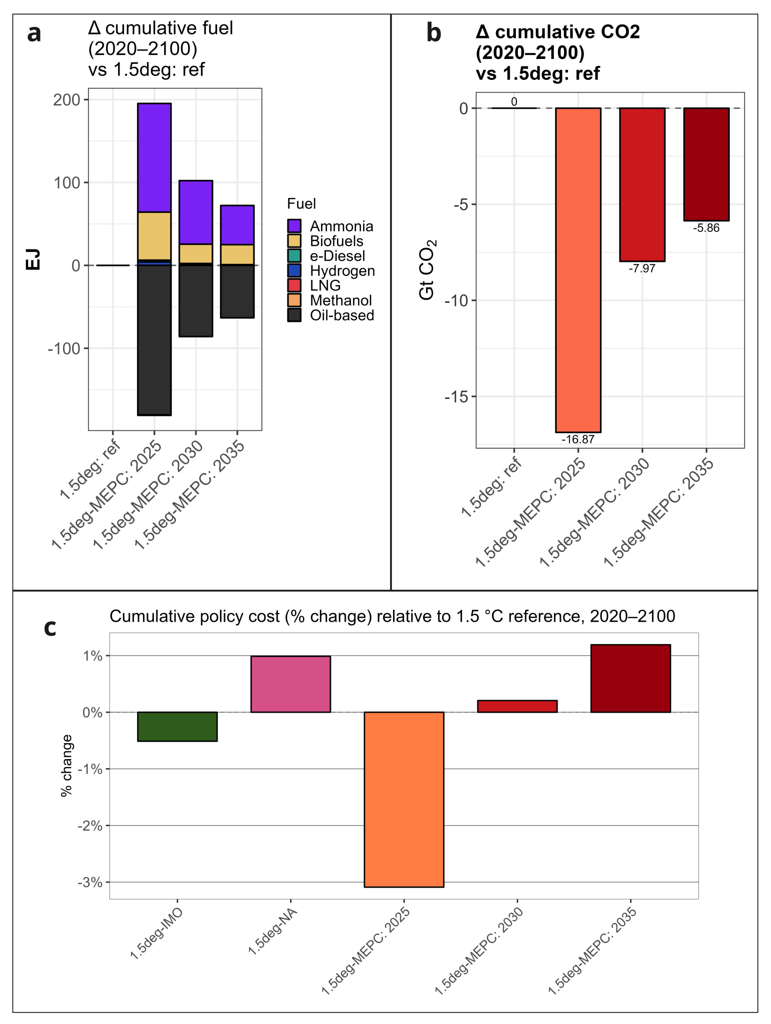

Figure 5.7.: **Testing the starting year of MEPC-83 NZF enforcement. a**, Change in cumulative fuel use over 2020–2100 relative to the 1.5deg reference scenario. **b**, Corresponding change in cumulative CO_2 emissions. **c**, Change in cumulative global policy cost, measured as GDP loss relative to the no-policy baseline, highlighting the increasing system-wide cost of delayed maritime regulation.

1.2%, implying an average penalty of about 0.4% per year of delay in the upcoming decade. As with emissions, the marginal cost of delay is highest in the initial years, reflecting lost opportunities for early learning, scale-up, and cost reduction.

Together, these results show that the effectiveness of the MEPC Net-Zero framework depends not only on its stringency but critically on timely implementation, with even short delays sharply eroding both emissions reductions and economic efficiency under a binding climate constraint.

5.4. DISCUSSIONS

A central insight emerging from this study is that the long-term decarbonisation of international shipping is not limited by demand growth or carbon-pricing stringency, but by the availability and scalability of genuinely zero-carbon marine fuels. Among the suite of candidates, ammonia consistently emerges as the only fuel capable of sustaining deep and rapid emissions reductions under stringent climate targets. Its advantage lies in a unique combination of features: it is zero-carbon at the point of use, it does not require carbon inputs in production, and it can be synthesised at an industrial scale using mature Haber–Bosch infrastructure powered by clean hydrogen. Whenever ammonia is available, it becomes the dominant fuel across all ambitious pathways; when it is excluded, the transition fragments into a costly mix of oil, biofuels, methanol, and marginal amounts of e-diesel and direct hydrogen, with LNG remaining limited to baseline conditions. This exclusion sharply increases fuel prices, delays decarbonisation by several decades, and more than triples cumulative emissions relative to the ammonia-enabled pathways. Methanol becomes the principal substitute in the no-ammonia case, while biofuels and e-diesel play complementary roles, yet none provide the cost-effectiveness or scale required for a rapid sector-wide transition. These results indicate that future debate should move beyond whether ammonia *will* be used and instead focus on *how* to deploy it safely and reliably, by addressing bottlenecks related to engine compatibility, NO_x control, port safety standards, and global bunkering networks.

The results also highlight the critical role of policy design, particularly the framework proposed under MEPC 83. When applied early, the Net-Zero Framework steers the sector toward a cost-effective, fully decarbonised trajectory without requiring extreme global carbon prices. Both the *baseline_MEPC* and *1.5 °C_MEPC* scenarios achieve rapid emissions reductions, with the latter reaching near-zero emissions by 2050 and aligning strongly with the 1.5 °C objective. The effectiveness of this policy architecture, however, depends critically on timing. Delaying implementation by only a few years sharply reduces its impact, halving cumulative clean-fuel uptake and emissions reductions over the century and increasing total system costs under a fixed carbon budget. Current delays therefore risk eroding the framework's ability to guide early investment, raising the cost of later corrective action, and locking in fossil-fuel technologies across the existing fleet. Moving from proposals to concrete regulatory action is thus essential for securing the sector's contribution to global climate goals and meeting the IMO’s 2050 ambition.

A central contribution of this study is the explicit quantification of cross-sector interactions triggered by maritime fuel choices. These interactions operate in two distinct directions. In *baseline*-based scenarios, shipping-specific levies raise fossil-fuel costs for vessels and pull biofuels and biomass away from road transport and industry, reducing their availability elsewhere. This effect is particularly evident in trends in biofuel consumption for road transport. In contrast, in 1.5 °C-based scenarios, the same levies accelerate early investment in green and blue hydrogen, as well as Haber–Bosch capacity. This induces economies of scale that reduce upstream hydrogen costs and enable technology spillovers into aviation and road transport. By the late century, these spillovers will increase the use of hydrogen and hydrogen-based fuels beyond shipping. The broader implication is that maritime decarbonisation cannot be analysed in isolation; sectoral choices reshape fuel allocation, technology learning, and mitigation burdens across the wider energy system.

System-wide cost and carbon-removal responses are consistent with these fuel-system dynamics. When ammonia is excluded, the economy requires substantially higher carbon removals, particularly from DACCS, because oil and biofuel use in shipping create additional residual emissions that must be offset elsewhere. In contrast, early ammonia deployment in the MEPC-aligned or IMO-forced 1.5 °C pathway lowers the need for BECCS and DACCS, reinforcing its value as a mitigation lever not only within the sector but across the entire energy system. Differences in hydrogen-supply investment indicate that meeting shipping targets within a 1.5,°C pathway is financially tractable: the additional capital required to enforce IMO-level ambition is comparable to a single year of today’s global fossil-fuel supply investment. Early investment in ammonia and blue–green hydrogen under the MEPC-aligned pathway acts as a system cost buffer, reducing long-run capital needs and limiting dependence on carbon-removal technologies.

Taken together, these findings offer three broad insights. First, scaling ammonia is essential for a credible and timely transition of international shipping. Second, early implementation of the MEPC 83 framework provides a feasible and cost-effective route to align the sector with the 1.5 °C target. Third, maritime decarbonisation generates wide-ranging spillovers, altering global hydrogen deployment, biofuel allocation, and carbon-removal requirements. A coordinated approach that acknowledges these interactions will be necessary to ensure that shipping contributes fully and efficiently to global climate mitigation while supporting, rather than disrupting, transitions in other sectors.

As with all integrated assessment modelling, these findings should be interpreted as scenario-based insights rather than forecasts. The results rest on assumptions regarding technology costs, resource availability, behavioural responses, and policy implementation that remain uncertain. Several processes relevant to real-world deployment, including port-side safety regulation, operational constraints, supply-chain bottlenecks, and short-term market dynamics, lie outside the scope of this modelling framework. Nonetheless, the multi-sector interactions, fuel-competition patterns, and system-wide investment responses observed here are robust across a wide range of parameter choices, providing a credible basis for interpreting how shipping decarbonisation may shape and be shaped by the wider energy transition. The explicit representation of international bunkers, fuel competition, and sectoral coupling offers a more realistic treatment of maritime activity within integrated assessment frameworks, addressing a long-standing gap in global modelling.

6

UNEVEN SEAS: REGIONAL RESPONSES

This chapter studies how global shipping decarbonization pathways unfold unevenly across regions within an integrated energy–economy–climate system. Building on the global results of the preceding chapter, it disaggregates outcomes by region to reveal how differences in trade structures, resource endowments, fuel availability, and policy exposure shape distinct transition trajectories. The chapter interprets how the same global climate signals propagate differently across regions through the integrated framework.
By doing so, this chapter closes the loop of the thesis. It connects the system-wide dynamics analysed in earlier chapters with region-specific feasibility, timing, and vulnerability, highlighting why global targets translate into heterogeneous regional outcomes.

6.1. INTRODUCTION

6.1.1. RECAP OF GLOBAL RESULTS

The previous chapter showed that global decarbonization in international shipping is shaped by three forces: the strength of economy-wide carbon pricing, the introduction of sector-specific measures such as the MEPC 83 package, and the availability of scalable zero-carbon fuels, most importantly ammonia. These factors determine how quickly oil-based fuels are displaced and whether the sector can align with the IMO 2050 ambition. The analysis also revealed that fuel choices in shipping could lead to substantial spillovers across the broader energy system, including shifts in hydrogen demand, biofuels allocation, and carbon-removal requirements. While these global pathways clarify the system-wide implications of maritime decarbonization, they mask regional differences. The following chapter examines these regional dimensions and how global policies translate into region-specific transitions.

6.1.2. MOTIVATION FOR REGIONAL ANALYSIS

International shipping operates through global networks, but regional fuel availability, trade structures, and economic conditions shape its decarbonization. Previous studies highlight that regional disparities in renewable energy potential, infrastructure readiness, and fuel costs strongly influence the adoption of alternative marine fuels [173, 213, 235]. For example, production costs for ammonia and methanol are projected to differ substantially across regions due to variation in renewable resource endowments, electricity prices, and supply-chain development [173, 236]. Similarly, shipping demand growth is expected to be concentrated in Asia, Africa, and other emerging economies, whereas mature markets such as Europe may experience stable trade volumes [84, 237]. These drivers suggest that the global transition will not occur uniformly and that regional perspectives are essential for understanding the sector's heterogeneous pathways.

The modeling framework used in this thesis explicitly accounts for such heterogeneity. In the WITCH-shipping model, fuel production costs depend on region-specific resource availability and electricity prices, while trade flows evolve according to regional production, consumption, and bilateral distance [238]. Fleet composition is also modelled at the regional level, allowing differences in vessel types and sizes to reflect distinct trade structures. This setup means that cross-regional contrasts in energy resource endowment, fuel costs, and demand growth are directly embedded in the results, rather than being inferred from global averages.

6.1.3. LINK TO POLICY RELEVANCE

Analyzing regional results highlights how global climate strategies interact with local conditions. Policymakers and industry stakeholders need to know whether certain regions will decarbonize earlier, face higher fuel costs, or remain dependent on transitional fuels. Such disparities can affect the competitiveness of regional fleets, determine the location of fuel-bunkering hubs, and raise questions about equity in sharing mitigation burdens. The International Maritime Organization underscored the importance of regionally differentiated impacts in its 2023 GHG strategy update [9], and integrated assessment studies confirm that uneven transitions across regions can reshape global energy markets and trade flows [196].

This chapter applies a five-region aggregation—Americas, Europe & CIS, Middle East & Africa, China, and Other Asia-Pacific, for both methodological and interpretive reasons. While the underlying WITCH model distinguishes 17 regions, analyzing each individually would add unnecessary detail and risk obscuring comparative insights. Grouping them into five macro-regions preserves regional heterogeneity while ensuring clarity and readability.

Comparability across regions was also a key consideration. The chosen groups capture broadly similar scales of trade demand, fuel use, and fleet composition, avoiding distortions that would otherwise make some regions appear disproportionately small or large. This enables meaningful comparisons of fuel-mix trajectories, emission reductions, and fleet transitions across scenarios.

Finally, the five regions reflect the main centers of global maritime trade and energy supply, with geography playing a decisive role in shaping shipping patterns. China and Other Asia-Pacific countries lie along the core East–West trade corridors and represent the center of future demand growth and fuel adoption. The Americas, with coastlines on both the Atlantic and Pacific, combine resource-rich exporters with major import markets. Europe & CIS link strong policy ambition with critical transit routes. The Middle East & Africa, positioned between the Mediterranean and Indian Ocean, combine abundant renewable energy resources with strategic chokepoints such as the Suez Canal and the Cape of Good Hope. This regional grouping is thus consistent with the modeling framework, while keeping results geographically clear, policy-relevant, and directly comparable. The regions used in this chapter are shown in Figure 6.1.

Table 6.1.: Mapping of macro-regions to model regions and represented countries.

Macro-Region	**Corresponding to model regions**	**Representing**
AMR	USA; CANADA; BRAZIL; LACA; MEXICO	USA; Canada; Mexico; Brazil; Latin America & Caribbean
ECS	EURO; TE(CIS)	European Union; UK; Norway; Switzerland; Non-EU Eastern Europe incl. Russia; Central Asia
APC	INDIA; SEASIA; SASIA; INDONESIA; OCEANIA; JPNKOR	India; Japan; Korea; Southeast Asia; South Asia; Indonesia; Australia; New Zealand
MEA	MENA; SSA; SA	Middle East & Africa (incl. South Africa)
CHN	CHINA	China (including Taiwan, Hong Kong, Macau)

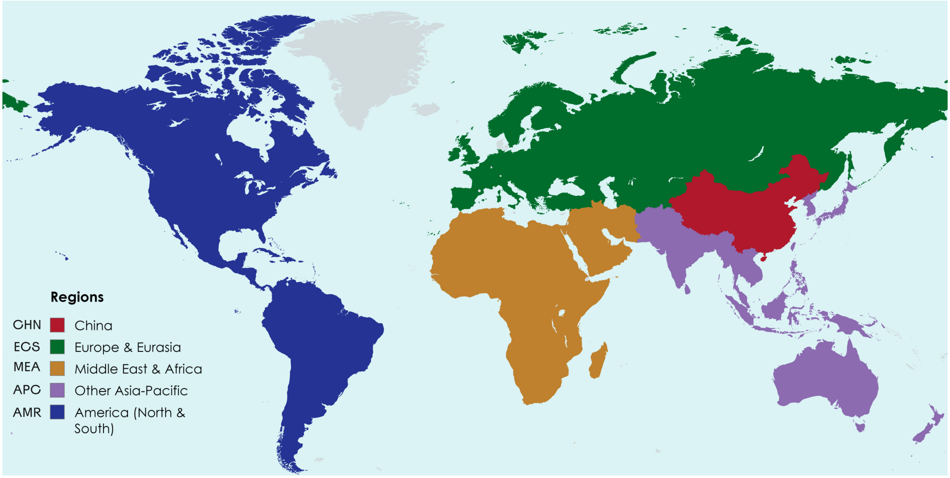

Figure 6.1.: Macro-regions considered in this chapter.

6.1.4. SCENARIOS

For the regional assessment, the six scenarios introduced in the previous chapter were reduced to five scenarios. Reducing the scenario set is necessary because regional analysis multiplies the number of comparisons and can easily become unreadable. The five selected scenarios preserve all policy signals and fuel constraints that generate meaningful regional differences, while avoiding unnecessary repetition. Two scenarios were removed because their regional behavior closely follows the 1.5 °C pathway. Although the additional constraints in those scenarios create useful contrasts at the global level, they do not yield new insights when disaggregated by region. In addition, one new scenario was introduced to capture fuel competition when ammonia is restricted, allowing us to observe how methanol and other alternatives scale once the primary zero-carbon option is removed.

The selected scenarios are as follows (Table 6.2). The *baseline* scenario represents the no-policy trajectory and provides the point of comparison for all regional outcomes. The 1.5 °C scenario applies a global carbon budget consistent with limiting warming to 1.5 degrees and reveals how economy-wide mitigation influences regional shipping. The 1.5 °C-*NA* scenario applies the same carbon budget while restricting ammonia, which highlights the role of this fuel in regional transitions. The *base-MEPC* scenario isolates the effect of the sector-specific levy proposed under the MEPC 83 process. The additional *base-MEPC-NA* scenario combines this regulation with an ammonia restriction, thereby exposing alternative fuel pathways once ammonia is excluded. Together, these five scenarios allow a clear comparison between global and sectoral policies and between pathways with and without ammonia.

Table 6.2.: Scenario mapping and policy dimensions

Scenario	Included in previous chapter	Global policy	Shipping taxation	Ammonia ban
baseline (BAU)	Yes	No policy	No	No
1.5 °C	Yes	Carbon budget	No	No
1.5 °C-*NA*	Yes	Carbon budget	No	Yes
base-MEPC	Yes	No policy	Yes	No
base-MEPC-NA	No	No policy	Yes	Yes

6.2. REGIONAL SHIPPING DEMAND & FUEL MIX

6.2.1. SHIPPING ACTIVITY DEMAND

Figure 6.2 shows the evolution of import-based international shipping demand across the five macro regions under the *baseline* and 1.5 °C pathways. Demand is expressed in trillion ton-miles per year. These two scenarios also represent the full set of scenarios, because the global emissions trajectory determines shipping activity and does not respond to sector-specific policies. The 1.5 °C and 1.5 °C-*NA* pathways therefore share the same demand profile, and the *base-MEPC* and *base-MEPC-NA* pathways follow the *baseline* profile. [1]

In the *baseline* scenario, import demand rises in all regions. CHN and APC have the highest levels throughout the century. AMR and ECS grow more moderately. MEA shows the fastest relative increase from a low starting point, and by 2100, its import demand is comparable to AMR and ECS, although it remains below CHN and APC. Under the 1.5 °C pathway, the global carbon budget reduces import demand in every region relative to the *baseline*. The largest absolute reductions occur in CHN and APC, where demand would otherwise expand most strongly. MEA still records substantial growth from its initial level, but its end-of-century imports are lower than in the unconstrained pathway.

Cargo composition differs clearly across regions and is broadly stable across the two pathways. AMR and ECS are dominated by container and minor bulk imports, followed by oil products. CHN stands out with a very large share of iron ore imports. APC has the most diverse portfolio, with substantial imports of coal, oil products, natural gas, and containers. MEA is characterized by a growing share of containerized and grain imports over time.

These patterns show that global mitigation dampens the overall scale of maritime trade of all cargo to different degrees, but does not alter the

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[1] Detailed results of each region is presented in figs. D.4 and D.5 in the appendix.

basic geography of import demand. CHN and APC remain the largest import centres, and MEA becomes an increasingly important destination in the long run.

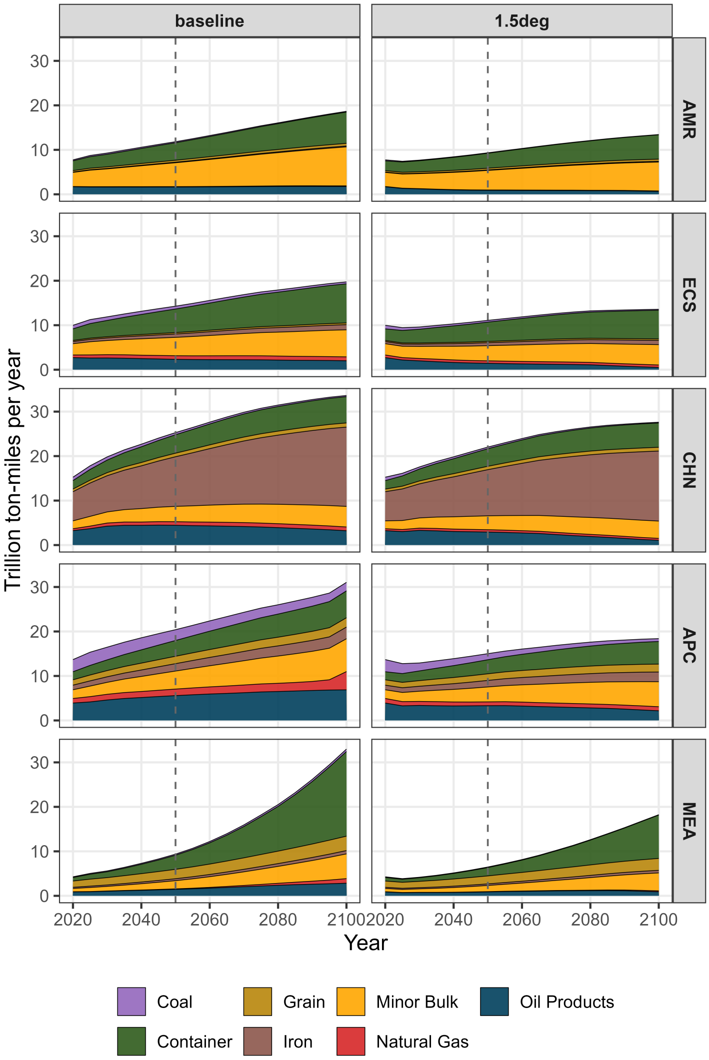

Figure 6.2.: Shipping activity demand of macro-regions under two main global trajectories.

6.2.2. MARINE FUEL MIX

Figure 6.3 shows how regional fuel use evolves under the five scenarios. The results reveal how economic structure, fuel availability, and regional resource conditions shape the pace and structure of the maritime transition. [2]

baseline

Without a climate policy, oil-based fuels remain dominant in every region throughout the century. The only meaningful deviation occurs in CHN, where oil scarcity emerges earlier than elsewhere and raises the opportunity cost of continued oil use. This pressure creates a relative price advantage for LNG, which expands gradually as a substitute. Other regions do not experience comparable constraints and therefore retain oil as the cost-effective option. The *baseline* pathway illustrates that in the absence of strong mitigation signals, fuel switching requires not only technological availability but also structural shifts in regional energy markets.

1.5 °C

Applying a global carbon budget produces a uniform transition toward ammonia across all regions. By mid-century, ammonia represents roughly half of the marine fuel mix in most regions and becomes nearly universal in the long run. CHN moves first, driven by tightening oil availability and strong incentives to invest in scalable alternatives. Early adoption encourages rapid diffusion and infrastructure build-out, which reinforces cost reductions through technological learning and shared production networks. MEA transitions more slowly because oil remains economically attractive for a longer period. The global convergence toward ammonia arises because the persistent carbon price eliminates the competitiveness of both oil and LNG, and because the coordinated expansion of ammonia production and bunkering infrastructure reduces relative costs simultaneously across regions. Under a stringent global mitigation effort, ammonia becomes the only fuel capable of sustaining deep decarbonization at scale.

1.5 °C-NA

Restricting ammonia fundamentally changes the structure and timing of regional transitions. All regions delay fuel switching, and no region reaches complete decarbonization by 2100. MEA is most affected and remains almost entirely dependent on oil because its abundant, low-cost reserves keep oil competitive even under the global carbon budget. Other regions diversify across methanol and biofuels, although the balance differs. ECS relies heavily on biofuels, reflecting higher biomass availability and lower opportunity costs. AMR and APC use both fuels,

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[2] Detailed results of each region is presented in figs. D.6 to D.10 in the appendix.

but neither alternative can match the scale or cost efficiency of ammonia. CHN invests primarily in methanol because it offers the most viable large-scale substitute within its regional resource constraints. Limited adoption of e-diesel is projected to occur late in the century in AMR and APC, as a complementary fuel rather than a dominant pathway. Direct hydrogen emerges only as a niche option for short-haul segments, consistent with storage limitations. The overall pattern shows that, without ammonia, the transition fragments and decarbonization slow down, with no single substitute emerging as a universally cost-effective solution.

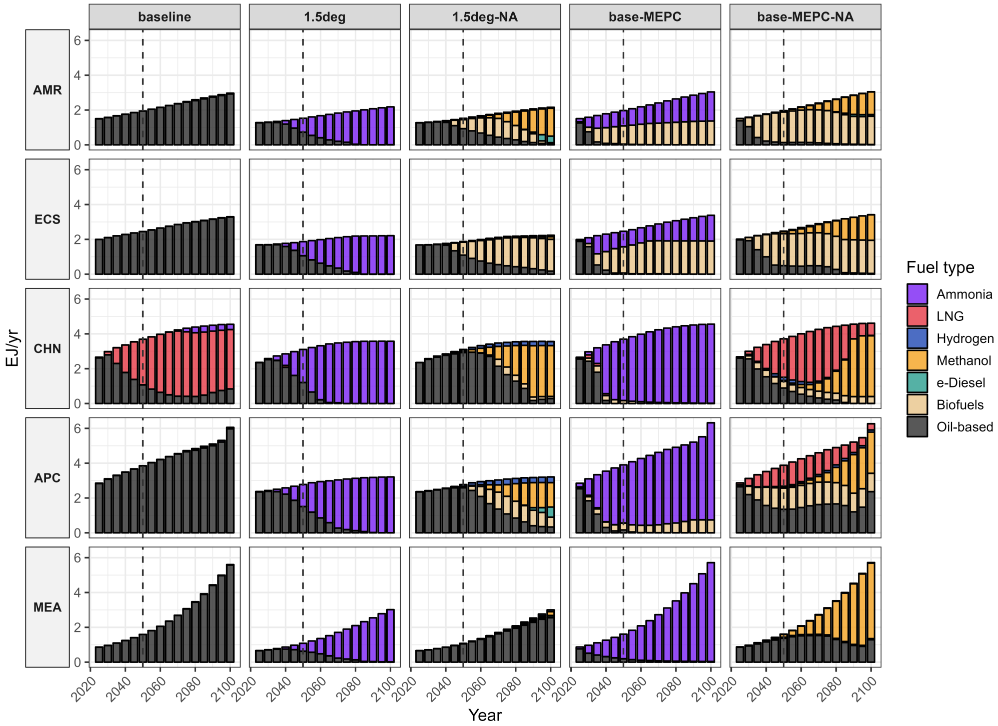

Figure 6.3.: Shipping fuel mix by macro-regions under scenarios.

base-MEPC

The sector-specific levy produces a rapid and synchronized transition across all regions. By 2050, the maritime sector will be nearly fully decarbonized across all regions, even without an economy-wide mitigation signal. The policy directly increases the operating costs of oil-fueled vessels, creating a strong incentive for early fuel switching and accelerating the retirement of high-emitting technologies. Most regions converge almost entirely to ammonia, reflecting its scalability and low well-to-wake emissions under targeted policy pressure. AMR and ECS rely more heavily on biofuels alongside ammonia because greater biomass availability lowers their relative cost. APC also uses biofuels, although primarily as a complementary option rather than a dominant pathway. MEA draws on its abundant renewable resources and, once the sectoral levy on fossil fuels is imposed, expands ammonia production at low cost. The MEPC 83 design imposes concentrated pressure on the maritime sector while leaving the rest of the economy largely untaxed, thereby preventing competition in clean fuels and infrastructure. This isolation effect allows shipping to adopt ammonia earlier and more decisively than under the global carbon budget alone.

base-MEPC-NA

Removing ammonia under a sector-specific levy creates a fragmented and slower transition. All regions face strong incentives to move away from oil, yet none can rely on a single scalable substitute. AMR and ECS are the least affected because biofuels cover a large share of their demand. Once biofuel availability reaches its limit, methanol expands gradually, allowing sufficient time to mature, as early demand pressure is modest. CHN and APC adopt a different strategy. Both deploy LNG at a large scale in the near and medium term to avoid the levy, and then supplement it with methanol and biofuels as these supply chains expand. CHN eventually closes most of the emissions gap through this multi-fuel approach and reaches near full decarbonization by 2100, similar to AMR and ECS. MEA shows the slowest transition. By 2050, it remains fully oil-based because its low-cost reserves remain competitive even under the levy. Only in the second half of the century does MEA redirect its renewable potential toward methanol production, which becomes its primary low-carbon fuel. The long-term consequences of the ammonia ban are most visible in APC and MEA, which both retain a substantial share of oil-based fuels by 2100. The scenario demonstrates that without ammonia, sector-specific regulation cannot generate a unified or rapid transition, and regions diverge according to their resource endowments and technological constraints.

Across all scenarios, three insights stand out. First, ammonia is the only fuel that enables a rapid and systemwide transition. When available, it becomes the dominant choice in both global and sector-specific policies, and regions converge regardless of their initial conditions. Second, removing ammonia exposes the limits of the remaining alternatives. Biofuels scale only where biomass is abundant, methanol expands slowly and cannot deliver complete decarbonization in high-demand regions, and LNG functions mainly as a temporary compliance strategy rather than a long-term solution. Third, policy design determines whether these regional differences narrow or widen. The global carbon budget forces convergence by reshaping relative fuel costs across the entire energy system, whereas the sector-specific levy induces rapid uptake only when a scalable zero-carbon fuel is available. When ammonia is excluded, the levy exacerbates regional disparities rather than reducing them.

6.3. AMMONIA AND METHANOL UPTAKE

The previous section showed that ammonia dominates the transition whenever it is permitted, and that methanol becomes relevant only when ammonia is excluded. This section examines these fuels in more detail. 1.5 °C and *base-MEPC* are analyzed for ammonia, and 1.5 °C-*NA* and *base-MEPC-NA* for methanol, since these are the only scenarios in which each fuel scales. figs. 6.4 and 6.5 show two dimensions: the distribution of global demand across regions and the dependence of each region on the fuel in its own mix. Together, these results clarify how policy design shapes both market leadership and regional exposure to specific fuels.

6.3.1. REGIONAL SHARES TO GLOBAL AMMONIA AND METHANOL MARKETS

Figure 6.4 shows how global ammonia and methanol demand are distributed across regions in the scenarios where each fuel becomes relevant. The patterns reveal how policy design shapes the geography of fuel production and whether leadership is concentrated in large economies or more evenly distributed across regions.

Under *base-MEPC*, ammonia demand is initially led by APC rather than CHN. The sector-specific levy induces a rapid early transition, and APC's combination of large maritime demand and fast switching gives it an early advantage. CHN overtakes APC around midcentury as its transition accelerates, but by 2100, MEA becomes the largest ammonia consumer. This shift reflects MEA's strong long-term expansion in shipping demand and its cost advantage in producing low-carbon fuels once fossil options are penalized. The sectoral policy therefore reallocates market influence away from the largest economies and toward regions with resource advantages and faster cost declines.

Under 1.5 °C, CHN holds the largest ammonia share in the early decades, followed by APC. This pattern reflects both regions' large underlying shipping demand and their relatively early adoption of ammonia. Over time, the distribution becomes more balanced as all regions converge toward full ammonia use. In contrast to the sector-specific levy, the global mitigation framework favors the largest economies rather than the fastest or lowest-cost adopters.

Methanol displays a similar contrast. Under 1.5 °C-*NA*, CHN and AMR dominate global methanol use, driven by their high maritime demand and their need for large-scale alternatives once ammonia is excluded.

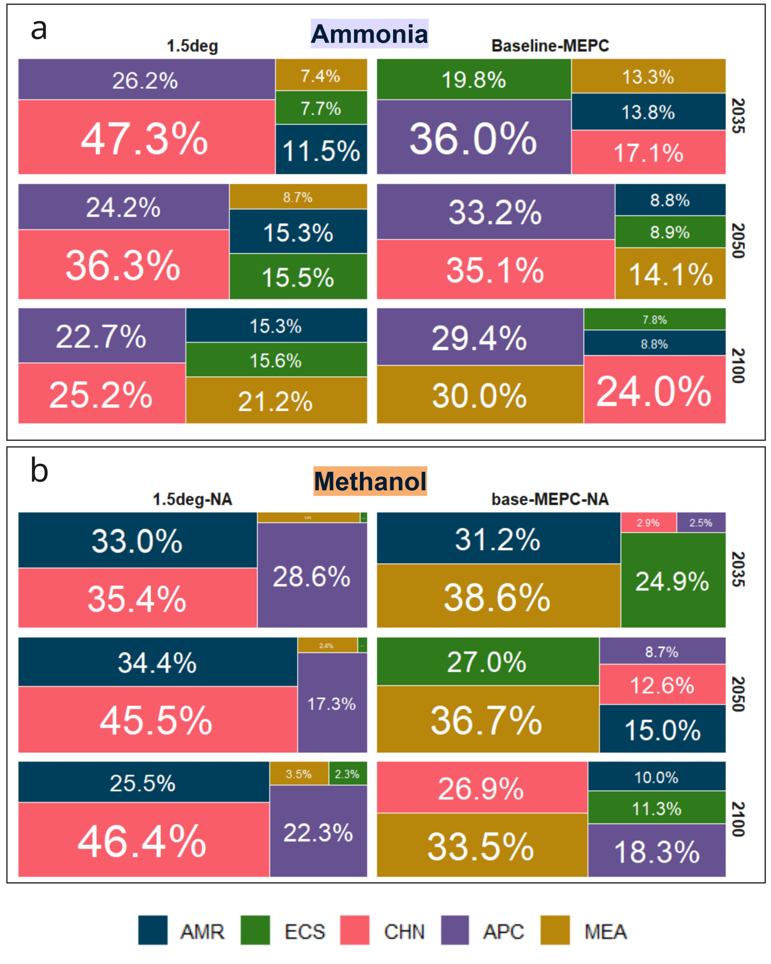

Figure 6.4.: Share of regions in global markets for **a**: ammonia and **b**: methanol for relevant scenarios.

MEA and ECS remain marginal users in this pathway. Under *base-MEPC-NA*, however, MEA becomes the dominant methanol consumer throughout the transition. APC, CHN, AMR, and ECS contribute meaningfully, but none match MEA's growth. In this scenario, the sector-specific levy favors regions with strong renewable potential and cost-effective fuel production rather than regions with the largest shipping activity.

Together, these results show a consistent pattern. Global mitigation tends to concentrate market share in large demand centers, while sector-specific regulation shifts leadership toward regions with structural cost advantages and faster transition dynamics. Policy design, therefore, not only shapes fuel choices but also determines which regions become the principal consumers of emerging maritime shipping fuels.

6.3.2. REGIONAL DEPENDENCE ON AMMONIA AND METHANOL

Figure 6.5 reports how strongly each region depends on ammonia or methanol within its own maritime shipping fuel mix. This measure reflects the extent to which a region commits to a single fuel pathway once the transition begins.

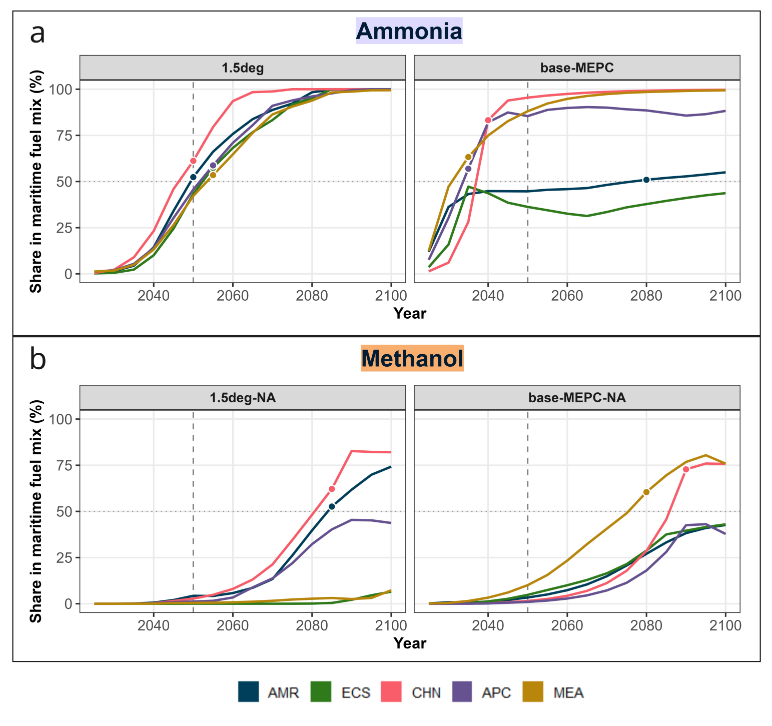

Figure 6.5.: Share of ammonia (**a**) and methanol (**b**) in regional maritime fuel mix, showing regions' dependencies on these fuels for relevant scenarios. Dots represent the year that share reaches 50%.

Under 1.5 °C, all regions increase their reliance on ammonia at a broadly similar pace. CHN and AMR reach approximately 50% ammonia share by 2050, reflecting both high demand and rapid early adoption. APC, ECS, and MEA follow a comparable trajectory and converge toward near full ammonia use later in the century. The global policy framework, therefore, produces a relatively uniform transition across regions. Under *base-MEPC*, regional patterns diverge more sharply. AMR and ECS rely less on ammonia because biofuels remain competitive given their greater biomass availability. Their ammonia share stabilizes at or below fifty percent. CHN and MEA, in contrast, reach complete dependence by 2100. APC also moves toward greater reliance on ammonia, though with a more gradual profile. The sector-specific levy thus produces a less uniform outcome than the global mitigation framework.

Methanol dependence evolves very differently. Even when ammonia is excluded, methanol plays only a minor role in all regions by 2050. This weak early uptake is caused by the need for carbon inputs in methanol production, which increases costs and complicates the process relative to ammonia production. However, under 1.5 °C-*NA*, methanol expands rapidly after mid-century. CHN, AMR, and APC substantially increase methanol use by the 2080s, and both CHN and AMR exceed 50% dependence. MEA and ECS continue to rely mainly on oil and biofuels, respectively. Under *base-MEPC-NA*, methanol growth is more uniform across regions, although MEA becomes the clear leader throughout the transition. MEA channels its renewable resources into methanol production once ammonia is unavailable, producing much faster growth than under the global carbon budget. CHN increases its methanol share later in the century and approaches MEA's trajectory. APC, AMR, and ECS adopt methanol at moderate levels. In contrast to the ammonia pathways, the sector-specific levy yields a more consistent rise in methanol dependence across regions, while the global policy framework concentrates methanol uptake in the largest economies.

These patterns underscore the structural difference between these two fuels. Ammonia enables rapid and uniform decarbonization when available, whereas methanol develops more slowly and unevenly due to its carbon input requirements and higher production costs. Policy design determines whether these differences amplify or narrow regional disparities.

6.4. REGIONAL EMISSION TRAJECTORIES

Figure 6.6 reports CO_2 and shipping emission intensity (CO_2 per ton-mile) reductions relative to the *baseline* scenario. CO_2 reductions reflect all drivers of emission change, including shifts in trade volumes and cargo composition, whereas emission intensity captures only improvements in fleet carbon performance. Comparing the two metrics reveals how policy design and fuel availability shape regional decarbonization pathways. [3]

Across both *base-MEPC* and *base-MEPC-NA* scenarios, CO_2 and emission intensity reductions track each other almost perfectly. This alignment indicates that the sector-specific levy operates almost entirely through the supply side: emissions decline because vessels switch fuels, not because regional trade patterns or transport demand change. The result

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[3] Absolute values of emissions are presented in fig. D.1 in the appendix.

Figure 6.6.: Regional shipping CO_2 (**a**), and emission intensity (CO_2/ton-mile, **b**) reduction compared to baseline scenario for 2030, 2050, and 2100.

is rapid fleet decarbonization, but limited variation across regions in the early decades since demand remains largely unaffected.

For 1.5 °C, the relationship between the two metrics is reversed in the early period. By 2030, CO_2 reductions are substantially larger than reductions in emission intensity across all regions. This divergence indicates that economy-wide mitigation lowers emissions initially through structural changes in the broader energy and trade systems and slower growth in activity, while the fleet transitions more gradually. Only after mid-century do emission intensity reductions catch up, reflecting the widespread adoption of ammonia and the eventual convergence of all regions toward a fully decarbonized fleet.

The ammonia-ban scenarios highlight where these two metrics decouple most strongly. In 1.5 °C-*NA*, several regions achieve noticeable CO_2 reductions by 2050 despite almost no improvement in emission intensity. CHN is an example: a 13% reduction in CO_2 emissions coexists with no change in emission intensity, implying that all progress comes from lower demand rather than from cleaner vessels. APC exhibits a similar pattern. These scenarios show that without ammonia, fleet decarbonization stalls even when overall emissions fall, and regional disparities persist well into the century.

Together, these results underscore the different mechanisms through which global and sector-specific climate policies operate. Global mitigation reduces emissions initially by reshaping economic activity, whereas sectoral regulation reduces emissions by altering the fleet fuel mix. Ammonia availability determines whether these two effects reinforce each other or diverge, and ultimately whether regions converge toward deep decarbonization or remain limited by structural constraints.

6.5. FLEET EVOLUTION BY REGION

The fuel mix results show which fuels dominate in each region, but they do not indicate how the transition is distributed across vessel classes. (Vessel classes and sizes are defined in Chapter 4.) Since vessels differ in size, emissions intensity, and operational roles, they do not transition at the same pace or toward the same technologies. Figure 6.7 presents the fleet composition in 2050, enabling us to examine how policy regimes and ammonia availability shape the technology mix across regions and vessel types [4]. The connection between cargo, vessels, fuels, and engines is illustrated in Figure B.5 in the appendix.

Across all scenarios, the pace of transition varies by vessel class, but early uptake is most common in segments with the highest emissions leverage. In several regions, small tankers tend to switch earlier because of their high emissions per unit of transport work, and some of the largest container classes begin transitioning sooner due to their large absolute contribution to total emissions. This pattern is visible in 1.5 °C, although with clear regional exceptions. CHN transitions its small tanker segment almost completely by 2050, while other regions move more gradually, and MEA shows limited adoption in large containerships (10%).

When ammonia is excluded (1.5 °C-*NA*), fleet transitions become narrow and uneven. CHN, APC, and MEA shift only their small tanker segments, mainly through fuel cells (FC) using direct hydrogen, while all

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[4] The results for 2030 and 2100 are presented in figs. D.2 and D.3 in the appendix.

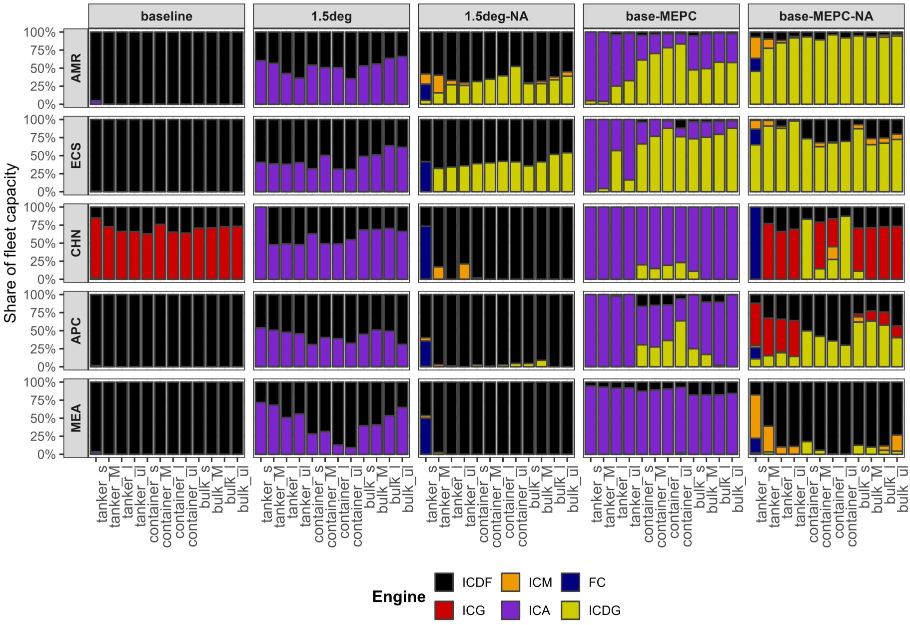

Figure 6.7.: Fleet composition for 2050, disaggregated by engines. Table 5.3 shows the engines' definitions.

other classes remain oil-based. AMR and ECS follow different pathways due to their access to biofuels: most of their transitions rely on drop-in fuels, starting with the largest ship classes. AMR also deploys methanol in tankers, and ECS uses some fuel cells in small tankers.

Under the sector-specific levy (*base-MEPC*), transitions are broader across all vessel types. AMR and ECS rely heavily on biofuels, especially in their container fleets. APC and CHN shift most classes to ammonia. MEA shows one of the most uniform transitions, with ammonia deployed in nearly all vessel classes except some bulker segments, where oil persists for longer.

In *base-MEPC-NA*, regional differences widen. ECS fully transitions its tanker fleet, while containers and bulkers still retain around one-third oil. AMR shows a structure similar to 1.5 °C-*NA*, but with much higher penetration, with most segments nearly fully decarbonized. CHN and APC use mixed strategies: LNG dominates CHN's tanker and container classes, supplemented by fuel cells in small tankers and biofuels in select container segments. APC mirrors this pattern, with LNG concentrated in tankers and biofuels in most other segments. MEA shows only a limited transition in small and medium tankers through methanol, while almost all other vessel types remain oil-based.

Together, these results show that early transitions concentrate in vessel classes that combine high emissions intensity or large absolute emissions with access to scalable zero-carbon fuels. figs. D.14 and D.15 provide additional information on the transition rates for vessel types and sizes across all regions and scenarios.

6.6. DISCUSSION

China (CHN) is the region that most strongly determines the global feasibility of maritime decarbonization. Its sheer scale of shipping demand means that its fuel choices shape global cost trajectories, infrastructure build-out, and technology learning. When ammonia is available, CHN transitions early and decisively, adopting ammonia at scale by mid-century and driving down global costs as deployment accelerates. This early leadership significantly reduces long-term system costs and enables rapid convergence among all regions. When ammonia is excluded, CHN faces the largest structural constraint: CO_2 reductions occur primarily through reduced activity under global mitigation, while the fleet itself remains oil-based for much longer because no alternative fuel can scale to the required magnitude. Under the sectoral levy without ammonia, CHN relies extensively on LNG as a compliance strategy and supplements this with targeted adoption of methanol, biofuels, and hydrogen in specific vessel segments. CHN's results underscore a critical insight: the global system converges only if its largest actor has access to a scalable fuel. Without ammonia, fragmentation persists, and decarbonization becomes slower, more complex, and more expensive.

Other Asia-Pacific (APC) represents the most structurally challenging environment for maritime decarbonization. The region's rapid expansion in container, energy, and bulk imports amplifies baseline emissions and increases the scale of required fuel switching. When ammonia is available, APC transitions effectively, particularly under the sector-specific levy, where strong price signals encourage early uptake. However, in ammonia-ban scenarios, APC exhibits one of the sharpest divergences between CO_2 and emission-intensity reductions. Activity growth overwhelms intensity improvements, and the fleet remains heavily oil-based across multiple vessel classes well into the century. Under the sectoral levy without ammonia, APC adopts LNG extensively in tanker segments and relies on biofuels in container fleets, yet oil persists because no available substitute can meet the scale of its growing demand. APC therefore demonstrates a central dynamic of maritime decarbonization: rapid demand growth magnifies the consequences of limited fuel diversity, making scalable zero-carbon fuels essential for high-growth regions.

Europe & CIS (ECS) performs consistently well across all policy regimes because its transition is shaped more by structural moderation than by fuel scarcity or rapid demand growth. The region benefits from relatively stable maritime activity and early access to biofuels, which together enable steady reductions in emission intensity, even in ammonia-restricted scenarios in which several other regions make little progress. ECS does not depend on a single fuel pathway: under global mitigation, it adopts ammonia at a measured but reliable pace, whereas under the sector-specific levy, it leans more heavily on biofuels and turns to methanol or hydrogen only when constraints force diversification. Fleet transitions begin in large-vessel classes, where efficiency gains yield the most significant payoff, whereas tanker segments are deferred if ammonia is unavailable. The main long-term uncertainty for ECS lies not in policy design but in the scalability of ammonia and the sustainable availability of biofuels, which may face increasing competition from land-based sectors. Overall, ECS demonstrates that moderate demand growth and a balanced fuel portfolio can deliver a stable, low-risk transition, even when global conditions diverge.

Americas (AMR) also follows a stable and resilient transition pathway. Its moderate growth in maritime demand means that fleet turnover and fuel switching unfold without the structural pressures seen in faster-growing regions. AMR benefits from comparatively strong access to bioenergy, which provides a reliable decarbonization route whenever ammonia is unavailable. As a result, AMR achieves some of the largest reductions in emission intensity in ammonia-restricted scenarios, whereas other regions struggle to decarbonize their fleets at all. Under the sector-specific levy, AMR moves early because biofuels function as immediate substitutes for oil, and ammonia adoption accelerates as it becomes competitive. Fleet transitions initially focus on larger container vessels, which yield the most significant emissions savings, whereas small tankers deploy hydrogen under more constrained pathways. AMR's trajectory demonstrates that fuel flexibility, supported by moderate demand growth, can deliver robust decarbonization even when global fuel constraints bind.

Middle East & Africa (MEA) shows the clearest distinction between decarbonization potential and realized outcomes. The region possesses abundant low-cost renewable resources, which enable highly competitive ammonia production when sector-specific policy is applied. Under these conditions, MEA transitions rapidly and eventually becomes one of the world's largest ammonia users, sometimes surpassing China in the long run. However, when ammonia is excluded, MEA becomes the slowest region to decarbonize. Low-cost oil remains competitive far into the century, and methanol adoption appears only later in selected tanker classes. MEA also exhibits some of the steepest divergences between CO_2 emissions and emission-intensity reductions because rising maritime demand offsets modest efficiency gains. MEA's trajectory highlights a fundamental insight: resource abundance alone does not guarantee decarbonization. The region achieves rapid progress only when a scalable zero-carbon fuel pathway exists. Without ammonia, MEA remains structurally locked into oil, showing that access to suitable fuels is a stronger determinant of transition outcomes than resource potential alone.

Globally, deep maritime decarbonization is feasible but not uniform, and its success depends on the alignment of three conditions: the availability of a scalable zero-carbon fuel, the strength and structure of policy signals, and the pace of underlying demand growth. Ammonia is the only fuel that enables full convergence across regions; when it is available, even fast-growing economies eventually transition, and sector-specific regulation accelerates this outcome. When ammonia is restricted, transitions fragment along regional resource lines, and no alternative pathway achieves complete decarbonization. High-growth regions, such as China and Other Asia-Pacific countries, are constrained by fuel scalability, while biofuel-rich regions, such as the Americas and Europe, maintain progress but cannot anchor the global system alone. The Middle East and Africa transition from an initially slow adopter to a central actor in the late-century fuel system, enabled by its renewable resource potential and expanding maritime demand. These outcomes show that decarbonization strategies must be globally coordinated yet regionally adaptive, as uniform policy signals yield markedly different outcomes across diverse maritime systems.

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CONCLUSION

The objective of this thesis has been to evaluate international shipping decarbonisation pathways from an integrated techno-economic perspective, examining how global and sectoral climate policies jointly shape fuel choices, costs, and emissions within a broader energy–economy system.

7.1. HIGHLIGHTS, CONTRIBUTIONS & CONCLUSIONS

Chapter 2 contributes by providing the first systematic and quantitative comparison of published shipping decarbonization scenarios. It clarifies how different assumptions and methodological choices lead to divergent futures and identifies the structural gaps that limit the ability of existing approaches to capture the interactions between trade development, fleet evolution, fuel supply, and climate policy. The chapter also sets out the criteria that a suitable modeling framework must meet to analyse these dynamics consistently at the global level. The review shows that the significant variation in projected shipping futures arises from differences in model structure, demand treatment, technology assumptions, and policy-scenario design. Sectoral models provide detailed representations of vessels and fuels but exclude feedbacks from trade and the broader energy system. Integrated Assessment Models (IAMs) capture these broader interactions but represent shipping too simply to assess fuel transitions or policy effects with confidence. As a result, most published scenarios cannot depict how trade, technology, and policy jointly shape long-term outcomes. The review also shows that most existing studies do not achieve complete decarbonization of shipping by 2050, highlighting both the scale of the problem and the limitations of current modeling with respect to ambitious targets. These findings motivate the framework developed in this thesis. Building on the WITCH IAM, a widely used and IPCC-assessed framework, this thesis introduces WITCH-shipping, a detailed extension that explicitly represents international maritime shipping. This provides the foundation for the modeling work developed in the subsequent chapters and throughout the thesis.

Chapter 3 extends the overall framework by replacing the common practice of treating shipping demand as exogenous or as a residual of energy balances in IAMs. It develops a mass-based, cargo-disaggregated bilateral trade model that represents existing seaborne trade categories and incorporates cross-trade flows, responding to income growth, oil price signals, and policy timing. This model is coupled directly within the integrated assessment framework so that shipping activity adjusts endogenously to climate policy. The model is calibrated and validated against a two-year global trade dataset and shows high predictive accuracy across major cargo categories, demonstrating that the structure is robust and suitable for scenario analysis. The results show that climate policy influences seaborne trade differently across cargo types and regions. Fossil fuel trades decline under stronger mitigation, while iron ore, containerised goods, grains, and minor bulks continue to evolve in line with economic and demographic trends. No new or speculative energy trade flows are introduced; future shipping activity is driven by changes in the volume and composition of established cargo categories. The analysis also shows that uncoordinated carbon pricing can temporarily redirect existing trade flows, as observed when early European taxation increased oil product trade before global adoption. These findings make clear that shipping demand cannot be represented as a single aggregate trend. This representation forms the basis for the next chapter, in which the resulting activity levels are translated into energy use, fuel requirements, and fleet development within the integrated framework.

Chapter 4 establishes the link between projected shipping activity, the corresponding energy demand, and fleet capacity. It allocates trade volumes to vessel types and size categories, and combines these with fuel consumption rates, productivity values, and lifetime parameters to estimate the total energy required for maritime transport across different scenarios. The mapping from trade flows to vessel classes is based on a bracketing method that uses shipping distance and cargo weight. This ensures consistency across cargo types and keeps the framework robust even as future trade structures change. These relationships are then used to determine the shipbuilding investments needed to meet future transport demand. The calibration relies on technical and operational parameters reported by the IMO. This chapter, therefore, establishes the quantitative link between activity, energy use, and fleet capacity, forming the basis for analysing fuel supply, fuel competition, and decarbonization pathways in the subsequent chapters.

Chapter 5 provides a unified framework in which shipping demand, fleet evolution, and fuel competition are represented consistently with the broader energy system. It also applies this framework to a quantitative assessment of the Net-zero framework proposed by MEPC-83[1], al-

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[1] This was recently delayed at a special meeting held in October 2025.

lowing its effects to be evaluated within a fully integrated model for the first time. The analysis relies on a calibration using 2020 baseline values for fuel mix, emissions, and vessel activity, and the future outcomes are derived from the optimisation of the WITCH model. The results show how global climate policy, sectoral regulation, and ammonia availability jointly determine the fuel mix, fuel costs, and emissions pathway of international shipping. A strong global carbon budget shifts the energy system toward green hydrogen and ammonia production and lowers the long-run cost of zero-carbon fuels. Sector-specific regulation, including the Net-zero framework proposed by MEPC-83, directly accelerates fuel switching by increasing the relative cost of fossil-fuel propulsion and accelerating fleet turnover. The results show that in baseline scenarios, shipping-specific policy can increase emissions in other transport sectors by diverting scarce biofuels and biomass away from road and industry, whereas in 1.5 °C pathways the same policies accelerate system-wide decarbonisation by inducing early hydrogen and ammonia investment that spills over into other transport sectors. For shipping, the availability of ammonia is central. When ammonia is permitted, it becomes the dominant zero-carbon fuel under stringent mitigation, enabling a complete phase-out of oil by mid-century at a manageable cost. When ammonia is excluded, the sector is forced to rely on more expensive alternatives such as methanol, biofuels, and e-diesel, which cannot scale sufficiently to meet long-term energy demand. This results in significant higher cumulative emissions. These findings establish how policy design and fuel availability interact to shape the global decarbonization pathway of international shipping. They also form the basis for Chapter 6, in which these global dynamics translate into distinct regional transitions and fuel pathways across the world.

The regional analysis in *Chapter 6* shows that international shipping does not decarbonize uniformly or in a synchronized manner because trade composition, fuel production costs, and economic structure differ across regions. This chapter presents the regional perspective of the same global model used in Chapter 5, examining how its regional outcomes unfold. China and other Asian-Pacific countries shift earliest under strong global carbon pricing. Still, they are also the most vulnerable to ammonia constraints, since the scale of their demand exceeds the ability of methanol, biofuels, or hydrogen to substitute at comparable cost. In contrast, the Americas, Europe, and CIS transition more steadily. They rely more on biofuels, supported by comparatively greater biomass availability, which allows continued progress even when ammonia is limited. The Middle East and Africa lag in development but, under strong sector-specific regulation, become major consumers and suppliers of ammonia or methanol, reflecting their renewable-resource potential and strategic position in global supply networks. Overall, the chapter shows that economy-wide climate policies tend to drive more uniform regional transitions over time, whereas sector-specific regulation produces more fragmented and heterogeneous regional outcomes, amplifying differences in resource endowments and demand structures. The analysis employs a modeling convention; Fuel use is allocated to regions based on imports, while in reality, bunker fuels are purchased and consumed through multi-port networks and are not attributable to a single regional energy balance.

Reflecting on the main research question: The thesis provides a modeling framework that links existing trade flows, energy use, fleet development, CO_2 emissions, and policy instruments in a single system, allowing decarbonization pathways to arise from the interactions among these elements rather than from external assumptions. The central implication is that effective maritime climate strategy requires coordinated policy, targeted support for scalable fuel production and an understanding that regions will follow different yet interconnected transition pathways. With this framework established, the thesis can now derive policy recommendations that follow directly from the model results.

7.2. POLICY RECOMMENDATION

From a policy perspective, the findings of this thesis suggest the need for more deliberate coordination between global and sectoral measures. Global carbon pricing should be paired with sector-specific instruments to ensure that zero-carbon fuels become both available and adopted in practice. Policymakers should prioritize stable and predictable regulatory signals, particularly for fuel standards and fleet renewal timelines, to support long-term investment decisions in vessels and bunkering infrastructure.

Ammonia safety and certification frameworks must be accelerated and internationally harmonized. Under any realistic pathway to net-zero shipping by mid-century, ammonia will be required on a large scale due to its energy density, storage capacity, and global production potential. The remaining safety and handling challenges are therefore constraints to be addressed, not arguments against adoption. Clear standards for toxicity management, bunkering operations, vessel design, and crew training are needed to enable the widespread deployment of ammonia with confidence and without compromising operational safety [65, 239].

The priority now should be implementation rather than further statements of intent. The shipping sector has a limited timeline to renew its fleet if it is to reach full decarbonization by 2050, and the global window to keep warming within 1.5 °C and well below 2 °C is narrowing each year. Because vessels and bunkering infrastructure have long lifetimes, postponing action today locks in emissions and reduces the feasibility of both targets. Ports, classification societies, and operators therefore require concrete and operational standards for bunkering systems, crew training, onboard monitoring, and incident response. These cannot remain theoretical. Early pilot operations and corridor-scale deployments are necessary to test procedures in real conditions, reveal operational and regulatory gaps, and accelerate learning-by-doing. Moving from rhetoric to applied practice builds confidence, reduces uncertainty, and makes the large-scale adoption of zero-carbon fuels technically and commercially viable.

Supporting fuel production in regions with strong renewable-resource potential, particularly in developing and emerging economies, must be recognized as a core element of global energy and industrial policy, not merely a shipping-sector concern. The regional results in Chapter 6 show that the Middle East & Africa becomes a central producer and consumer of ammonia under sectoral regulation, and the largest methanol user when ammonia is constrained, reflecting its abundant renewable energy potential and strategic position in global trade networks. If zero-carbon fuels are to scale at the volumes required for deep decarbonization, production cannot remain concentrated in a few high-income exporters [21, 240]. Without targeted access to finance, risk guarantees, and technology transfer, investment will flow only to already advantaged regions, reinforcing existing disparities and constraining global supply. Therefore, public and multilateral institutions must design financing, insurance, and partnership mechanisms that enable emerging regions to build viable production capacity. This is necessary both to ensure a sufficient global supply of zero-carbon fuels and to avoid a situation in which shipping decarbonization is slowed simply because too few regions can produce these fuels at scale.

European policymakers should adopt a sequenced strategy that balances near-term feasibility with long-term system needs. In the short term, regional biofuel potential offers the fastest emissions reduction because these fuels can be used as direct drop-ins and rely on existing infrastructure. Europe already has established biomass supply chains and conversion capacity, and using these effectively helps prevent unnecessary persistence of fossil bunkers. Over the long term, however, biofuels cannot provide the scale for full decarbonization. Achieving that outcome depends on accelerating green ammonia production, storage, and bunkering capacity, and ensuring that maritime demand planning is aligned with Europe’s broader industrial and power-sector strategies. A coherent policy pathway, therefore, combines immediate biofuel deployment with early investment and standardization of ammonia, avoiding competition for limited resources and ensuring that the sector can transition at the required scale and pace.

Finally, maritime decarbonization should be treated as part of the global energy transition rather than as a stand-alone sectoral issue. Coordination between the IMO, national governments, port authorities, and financial institutions is required to align fuel infrastructure development with evolving trade patterns and to anticipate shifts in bunkering geography as new fuels scale. Treating shipping, fuel production, and port infrastructure planning together allows governments and industry to identify where supply chains may fail, where new capacity is needed, and where existing assets risk becoming stranded. Strategic planning at this interface reduces transition risks and prevents bottlenecks before they emerge.

7.3. LIMITATIONS

The framework developed in this thesis inevitably entails several limitations that shape the interpretation of the results.

First, the econometric estimation of trade elasticities relies on historical trends. If global trade structures shift due to reshoring, supply chain diversification, or geopolitical realignment, these elasticities may evolve. While the model robustly captures directional responses, its quantitative estimates depend on the assumption that past structural drivers remain informative for the future. **Second**, technological performance and cost trajectories for emerging fuels such as ammonia, methanol, and hydrogen remain uncertain. Learning rates and future policy support are difficult to anticipate, and different assumptions could influence the relative competitiveness of different decarbonization pathways. The scenarios should therefore be understood as structured explorations rather than predictions of specific fuel shares. **Third**, the spatial and operational representation of shipping is simplified. The model uses regional aggregation, which smooths over intra-regional variation in port infrastructure, routing constraints, and corridor-level dynamics. In addition, shipping activity is represented as bilateral exchanges between regions, and fuel use is attributed to the importing region for accounting consistency. In practice, maritime transport operates through multi-port routes, transshipment hubs, and globally traded bunkering markets that are not naturally associated with any single region's energy balance. This simplification is necessary for integration with a global energy and economy model but does not fully reflect the operational and institutional complexity of international shipping. This represents one of the two main modeling limitations of the framework.

Fourth, the other main modeling limitation is that the model does not include a feedback loop from marine fuel costs to trade flows. In the current configuration, the trade model responds to oil prices because historical fuel use in shipping is almost entirely oil-based, and these elasticities reflect that history. Within the WITCH model, fuel prices are determined endogenously through system optimization and are calculated ex post rather than supplied as inputs to the trade equations. As a result, changes in the cost of zero-carbon fuels do not feed back into trade volumes. **Finally**, the model does not explicitly represent behavioral and institutional dynamics, including shipowner investment strategies, chartering arrangements, fuel contracting practices, or real-time operational decision-making. These factors, while out of scope for this research, can shape transition timing, especially in the near term. The results, therefore, reflect system-level economic incentives rather than individual decision-making processes.

For these reasons, the findings presented in this thesis should be interpreted as comparative insights into the long-term interaction between trade, technology, and policy rather than as precise forecasts. The framework is designed to clarify the mechanisms by which global mitigation policy and fuel availability influence maritime decarbonization pathways, rather than to predict exact outcomes under any single scenario. Despite these limitations, the integrated structure provides a coherent and scientifically grounded basis for examining how policy design, resource endowments, and trade patterns jointly shape the feasibility and timing of shipping's transition.

7.4. FUTURE RESEARCH

Future research can extend the framework developed in this thesis to mitigate the limitations outlined above. With regard to **Limitation 1**, the trade model should be periodically re-estimated as global trade patterns evolve. This is particularly important as supply chains diversify, energy commodities phase down, and strategic trade relationships shift under decarbonization. Regular recalibration would ensure that the representation of shipping demand remains empirically grounded. For **Limitation 2**, uncertainty in the cost and performance of emerging fuels can be explored through coordinated multi-model comparison. Implementing the maritime module in other integrated assessment models such as IMAGE[74], GCAM[96], or TIAM[77] enables testing of results under various system structures and learning assumptions, helping to identify which results are model-dependent and which are more general. For **Limitation 3**, increasing spatial resolution to the level of major ports, port clusters, or trade corridors, and linking the framework with routing or network optimization models, would allow the representation of transshipment dynamics, infrastructure bottlenecks, and evolving bunkering geography as alternative fuels scale. This would also support more realistic regional attribution of fuel consumption and emissions.

Regarding **Limitation 4**, introducing a feedback mechanism through which maritime fuel costs influence trade volumes would allow trade patterns and fuel transitions to co-evolve. This could be achieved either by iteratively linking the trade equations to the energy system optimization or by embedding generalized transport-cost elasticities directly into the trade model. Finally, addressing **Limitation 5** would require incorporating heterogeneous decision-making. Linking the integrated framework to investment models or agent-based representations would enable the explicit modeling of fleet owners, charterers, and operators with different risk profiles. Including scenarios with geopolitical or supply-chain shocks would further enable assessment of resilience alongside decarbonization outcomes.

As noted by the IPCC, “Every action matters. Every year matters. Every choice matters.” The modeling framework developed here provides not only scientific insight but also a tool to inform these choices, guiding policymakers and industry toward pathways that keep the world’s oceans and its future on a sustainable course.

BIBLIOGRAPHY

[1] IPCC. *Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report*. Ed. by H. Lee and J. Romero. Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2023. doi: `10.59327/IPCC/AR6-9789291691647`.

[2] H. Lee, J. Romero, *et al.* "Climate change 2023: Synthesis report". In: *A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2023).

[3] IEA. *International Shipping*. Report. International Energy Agency, 2020. url: `https://www.iea.org/reports/international-shipping`.

[4] IMO. *Fourth IMO GHG study 2020*. Journal Article. 2020.

[5] T. R. Walker, O. Adebambo, M. C. Del Aguila Feijoo, E. Elhaimer, T. Hossain, S. J. Edwards, C. E. Morrison, J. Romo, N. Sharma, S. Taylor, and S. Zomorodi. "Environmental Effects of Marine Transportation". In: *World Seas: an Environmental Evaluation* (2019).

[6] W. T. O. .-. WTO. *International trade statistics*. Dataset. 2021. url: `https://data.wto.org`.

[7] IMO. *Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG emissions in the shipping sector*. International Maritime Organization, 2018.

[8] R. Schnurr and T. R. Walker. "Marine transportation and energy use". In: *Reference Module in Earth Systems and Environmental Sciences; Elsevier: Amsterdam, The Netherlands* (2019), pp. 1–9.

[9] IMO. *Revised GHG reduction strategy for global shipping adopted*. 2023. url: `https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx`.

[10] P. Balcombe, J. Brierley, C. Lewis, L. Skatvedt, J. Speirs, A. Hawkes, and I. Staffell. "How to decarbonize international shipping: Options for fuels, technologies, and policies". In: *Energy conversion and management* 182 (2019), pp. 72–88. issn: 0196-8904.

[11] H. N. Psaraftis. “The future of maritime transport”. In: *International Encyclopedia of Transportation; Elsevier: Amsterdam, The Netherlands* (2021), pp. 535–539.

[12] J. Wieckowski and Z. Szyjewski. “Practical study of selected multi-criteria methods comparison”. In: *Procedia Computer Science* 207 (2022), pp. 4565–4573.

[13] B. Hare, R. Brecha, and M. Schaeffer. “Integrated assessment models: What are they and how do they arrive at their conclusions”. In: *Clim. Anal* (2018), pp. 1–12.

[14] C. De Vincenti. “‘Baumol’S Disease’, Production Externalities And Productivity Effects Of Intersectoral Transfers”. In: *Metroeconomica* 58.3 (2007), pp. 396–412.

[15] M. Murat and F. Pigliaru. “International trade and uneven growth: a model with intersectoral spillovers of knowledge”. In: *Journal of International Trade & Economic Development* 7.2 (1998), pp. 221–236.

[16] H. Xing, C. Stuart, S. Spence, and H. Chen. “Alternative fuel options for low carbon maritime transportation: Pathways to 2050”. In: *Journal of Cleaner Production* 297 (2021), p. 126651. issn: 0959-6526.

[17] K. Esmeijer, M. den Elzen, and H. van Soest. “Analysing international shipping and aviation emission projections”. In: *PBL Publication* 4076 (2020).

[18] E. Müller-Casseres, O. Y. Edelenbosch, A. Szklo, R. Schaeffer, and D. P. van Vuuren. “Global futures of trade impacting the challenge to decarbonize the international shipping sector”. In: *Energy* 237 (2021), p. 121547. issn: 0360-5442.

[19] A. C. Köberle. “The value of BECCS in IAMs: a review”. In: *Current Sustainable/Renewable Energy Reports* 6 (2019), pp. 107–115.

[20] M. M. Elgohary, I. S. Seddiek, and A. M. Salem. “Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel”. In: *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 229.4 (2015), pp. 365–375. issn: 1475-0902.

[21] O. B. Inal, B. Zincir, and C. Deniz. “Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia”. In: *International Journal of Hydrogen Energy* 47.45 (2022). issn: 0360-3199.

[22] M. D. B. Watanabe, F. Cherubini, and O. Cavalett. “Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment”. In: *Journal of Cleaner Production* 364 (2022), p. 132662.

[23] J. D. Ampah, A. A. Yusuf, S. Afrane, C. Jin, and H. Liu. “Reviewing two decades of cleaner alternative marine fuels: Towards IMO’s decarbonization of the maritime transport sector”. In: *Journal of Cleaner Production* 320 (2021), p. 128871. issn: 0959-6526.

[24] D. Kramel, H. Muri, Y. Kim, R. Lonka, J. B. Nielsen, A. L. Ringvold, E. A. Bouman, S. Steen, and A. H. Strømman. “Global Shipping Emissions from a Well-to-Wake Perspective: The MariTEAM Model”. In: *Environmental Science & Technology* 55.22 (2021), pp. 15040–15050.

[25] H. Yang, X. Ma, and Y. Xing. “Trends in CO2 emissions from China-oriented international marine transportation activities and policy implications”. In: *Energies* 10.7 (2017), p. 980. issn: 1996-1073.

[26] E. Müller-Casseres, F. Carvalho, T. Nogueira, C. Fonte, M. Império, M. Poggio, H. K. Wei, J. Portugal-Pereira, P. R. Rochedo, and A. Szklo. “Production of alternative marine fuels in Brazil: An integrated assessment perspective”. In: *Energy* 219 (2021), p. 119444. issn: 0360-5442.

[27] S. Less, R. McIlveen, and D. Helm. “Greener, Cheaper”. In: *Policy Exchange, London* (2010).

[28] G. Nikolakaki. “Economic incentives for maritime shipping relating to climate protection”. In: *WMU Journal of Maritime Affairs* 12.1 (2013), pp. 17–39. issn: 1654-1642.

[29] K. Anderson, I. Stoddard, and J. Schrage. *Carbon budget and pathways to a fossil-free future in Järfälla Municipality*. Generic. 2017.

[30] D. Harrison, D. Radov, J. Patchett, P. Klevnas, A. Lenkoski, P. Reschke, and A. Foss. “Economic instruments for reducing ship emissions in the European Union”. In: *NERA Economic Consulting, London, UK* 30 (2005).

[31] S. Lagouvardou, H. N. Psaraftis, and T. Zis. “Impacts of a bunker levy on decarbonizing shipping: A tanker case study”. In: *Transportation Research Part D: Transport and Environment* 106 (2022), p. 103257. issn: 1361-9209.

[32] S. Lagouvardou and H. N. Psaraftis. “Implications of the EU Emissions Trading System (ETS) on European container routes: A carbon leakage case study”. In: *Maritime Transport Research* 3 (2022), p. 100059. issn: 2666-822X.

[33] European Commission. *Reducing emissions from the shipping sector*. 2023. url: `https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en`.

[34] Transport and Environment. *Statistical analysis of the energy efficiency performance (EEDI) of new ships built in 2013-2017*. Generic. 2018.

[35] DNV. *Maritime forecast to 2050*. Report. DNV, 2021.

[36] F. Khosravi and U. Jha-Thakur. "Managing uncertainties through scenario analysis in strategic environmental assessment". In: *Journal of Environmental Planning and Management* 62.6 (2019).

[37] UNCTAD. *Review of maritime transport*. New York: United Nations Publications, 2022. isbn: 978-92-1-113073-7.

[38] Clarksons Research. *World Seaborne Trade Tables*. Accessed: 2023-07-01. Shipping Intelligence Network. 2022. url: `https://sin.clarksons.net`.

[39] H. Meersman and E. Van de Voorde. "The relationship between economic activity and freight transport". In: *Freight transport modelling*. Emerald Group Publishing Limited, 2013, pp. 15–43.

[40] K. Riahi, D. P. Van Vuuren, E. Kriegler, J. Edmonds, B. C. O'neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, *et al.* "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview". In: *Global environmental change* 42 (2017), pp. 153–168.

[41] DNV. *Maritime forecast to 2050*. Report. DNV, 2018.

[42] C. Walsh, N.-J. Lazarou, M. Traut, J. Price, C. Raucci, M. Sharmina, P. Agnolucci, S. Mander, P. Gilbert, and K. Anderson. "Trade and trade-offs: Shipping in changing climates". In: *Marine Policy* 106 (2019), p. 103537. issn: 0308-597X.

[43] R. A. Halim, L. Kirstein, O. Merk, and L. M. Martinez. "Decarbonization pathways for international maritime transport: A model-based policy impact assessment". In: *Sustainability* 10.7 (2018), p. 2243. issn: 2071-1050.

[44] V. Eyring, H. Köhler, A. Lauer, and B. Lemper. "Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050". In: *Journal of Geophysical Research: Atmospheres* 110.D17 (2005). issn: 0148-0227.

[45] N. A. Michail. "World economic growth and seaborne trade volume: quantifying the relationship". In: *Transportation Research Interdisciplinary Perspectives* 4 (2020), p. 100108. issn: 2590-1982.

[46] L. Martinez, J. Kauppila, and M. Castaing. "International freight and related CO2 emissions by 2050: A new modelling tool". In: International Transport Forum Discussion Paper. 2014.

[47] S. E. Masten. “Long-term contracts and short-term commitment: Price determination for heterogeneous freight transactions”. In: *American Law and Economics Review* 11.1 (2009), pp. 79–111.

[48] J. Mason, A. Larkin, S. Bullock, N. van der Kolk, and J. F. Broderick. “Quantifying voyage optimisation with wind propulsion for short-term CO2 mitigation in shipping”. In: *Ocean Engineering* 289 (2023), p. 116065.

[49] DNV. *Maritime forecast to 2050*. Report. 2022. url: `https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html`.

[50] G. Horton, H. Finney, S. Fischer, I. Sikora, J. McQuillen, N. Ash, and H. Shakeel. *Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050*. Report. Ricardo Energy & Environment, 2022.

[51] T. Smith, C. Raucci, S. H. Hosseinloo, I. Rojon, J. Calleya, S. S. De La Fuente, P. Wu, and K. Palmer. “CO2 emissions from international shipping: Possible reduction targets and their associated pathways”. In: *UMAS: London, UK* (2016).

[52] UNCTAD. *Review of maritime transport*. New York: United Nations Publications, 2021. isbn: 978-92-1-113026-3.

[53] J. Herdzik. “Decarbonization of marine fuels—The future of shipping”. In: *Energies* 14.14 (2021), p. 4311. issn: 1996-1073.

[54] L. C. Law, B. Foscoli, E. Mastorakos, and S. Evans. “A comparison of alternative fuels for shipping in terms of lifecycle energy and cost”. In: *Energies* 14.24 (2021), p. 8502. issn: 1996-1073.

[55] H. Brauers, I. Braunger, and J. Jewell. “Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions”. In: *Energy Research & Social Science* 76 (2021).

[56] S. Bengtsson, K. Andersson, and E. Fridell. “A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels”. In: *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 225.2 (2011), pp. 97–110.

[57] D. F. Van der Kroft and J. F. Pruyn. “A study into the availability, costs and GHG reduction in drop-in biofuels for shipping under different regimes between 2020 and 2050”. In: *Sustainability* 13.17 (2021), p. 9900. issn: 2071-1050.

[58] ABS. *Setting the Course to LowCarbon Shipping: Zero Carbon Outlook*. 2022. url: `https://ww2.eagle.org/en/publication-flip/zero-carbon-outlook.html`.

[59] L. Register. “Low Carbon Pathways 2050”. In: *Sustainability, Editor* (2016).

[60] S. Franz, N. Campion, S. Shapiro-Bengtsen, R. Bramstoft, D. Keles, and M. Münster. “Requirements for a maritime transition in line with the Paris Agreement”. In: *Iscience* 25.12 (2022).

[61] E. Müller-Casseres, F. Leblanc, M. van den Berg, P. Fragkos, O. Dessens, **Naghash, Hesam**, R. Draeger, T. Le Gallic, I. S. Tagomori, I. Tsiropoulos, *et al.* “**International shipping in a world below 2° C**”. In: *Nature Climate Change* 14.6 (2024), pp. 600–607.

[62] R. Carlo, B. J. Marc, S. de la Fuente Santiago, T. Smith, and K. Søgaard. “Aggregate investment for the decarbonization of the shipping industry”. In: *UMAS, London, UK* (2020).

[63] B. Stolz, M. Held, G. Georges, and K. Boulouchos. “Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe”. In: *Nature Energy* 7.2 (2022), pp. 203–212.

[64] IRENA. *A pathway to decarbonize the shipping sector by 2050*. Tech. rep. Abu Dhabi: International Renewable Energy Agency, 2021.

[65] DNV. *Maritime forecast to 2050*. Report. DNV, 2023.

[66] M. S. Eide, C. Chryssakis, and Ø. Endresen. “CO2 abatement potential towards 2050 for shipping, including alternative fuels”. In: *Carbon Management* 4.3 (2013), pp. 275–289.

[67] L. Register and UMAS. *Techno-Economic Assessment of Zero-Carbon Fuels*. 2020.

[68] H. Wang and N. Lutsey. “Long-term potential for increased shipping efficiency through the adoption of industry-leading practices”. In: *The International Council on Clean Transportation* 65 (2013).

[69] UN. *SDG 13 Issue Brief: Sustainable Development Goal 13 (SDG 13) - Promote Mechanisms for Raising Capacity for Effective Climate Change-related Planning and Management in Least Developed Countries and Small Island Developing States, including Focusing on Women, Youth and Local and Marginalized Communities*. 2019. url: `https://wedocs.unep.org/20.500.11822/28448`.

[70] J. Rogelj, W. Hare, J. Lowe, D. P. Van Vuuren, K. Riahi, B. Matthews, T. Hanaoka, K. Jiang, and M. Meinshausen. “Emission pathways consistent with a 2 C global temperature limit”. In: *Nature Climate Change* 1.8 (2011), pp. 413–418.

[71] P. R. Rochedo, B. Soares-Filho, R. Schaeffer, E. Viola, A. Szklo, A. F. Lucena, A. Koberle, J. L. Davis, R. Rajão, and R. Rathmann. “The threat of political bargaining to climate mitigation in Brazil”. In: *Nature climate change* 8.8 (2018), pp. 695–698.

[72] P. R. R. Rochedo. “Development of a global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios”. In: *DS Thesis, Universidade Federal do Rio de Janeiro, Brazil* (2016).

[73] H. Waisman, C. Guivarch, F. Grazi, and J. C. Hourcade. “The I maclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight”. In: *Climatic Change* 114 (2012), pp. 101–120.

[74] D. P. Van Vuuren, M. Kok, P. L. Lucas, A. G. Prins, R. Alkemade, M. van den Berg, L. Bouwman, S. van der Esch, M. Jeuken, T. Kram, *et al.* “Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model”. In: *Technological Forecasting and Social Change* 98 (2015), pp. 303–323.

[75] E. Stehfest, D. van Vuuren, T. Kram, L. Bouwman, R. Alkemade, M. Bakkenes, H. Biemans, A. Bouwman, M. den Elzen, J. Janse, P. Lucas, J. van Minnen, C. Müller, and A. Prins. *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications*. Technical Report. PBL Netherlands Environmental Assessment Agency, 2014.

[76] E3 Modelling. *PROMETHEUS Model Documentation*. 2018. url: `https://e3modelling.com/modelling-tools/prometheus/`.

[77] S. Pye, I. Butnar, J. Cronin, D. Welsby, J. Price, O. Dessens, B. S. Rodríguez, M. Winning, G. Anandarajah, D. Scamman, and I. Keppo. *The TIAM-UCL Model (Version 4.1.1) Documentation*. Technical Report Version 4.1.1. UCL Energy Institute, 2020.

[78] J. Emmerling, L. Drouet, L. Reis, M. Bevione, L. Berger, V. Bosetti, S. Carrara, E. De Cian, G. De Maere D’Aertrycke, T. Longden, *et al. The WITCH 2016 model-documentation and implementation of the shared socioeconomic pathways*. 2016.

[79] V. Bosetti, E. Massetti, and M. Tavoni. *The WITCH model: structure, baseline, solutions*. 2007.

[80] E. Müller-Casseres, A. Szklo, C. Fonte, F. Carvalho, J. Portugal-Pereira, L. B. Baptista, P. Maia, P. R. Rochedo, R. Draeger, and R. Schaeffer. “Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil”. In: *Iscience* 25.10 (2022).

[81] P. Agreement. “UNFCCC, Adoption of the Paris Agreement. COP”. In: *25th session Paris* 30 (2015), pp. 1–25.

[82] B. Hackmann. "Analysis of the governance architecture to regulate GHG emissions from international shipping". In: *International Environmental Agreements: Politics, Law and Economics* 12 (2012), pp. 85–103.

[83] UNCTAD. *Review of maritime transport*. New York: United Nations Publications, 2021. isbn: 978-92-1-113026-3.

[84] UNCTAD. *Review of maritime transport*. New York: United Nations Publications, 2022. isbn: 978-92-1-113073-7.

[85] International Energy Agency. *International Shipping*. https://www.iea.org/energy-system/transport/international-shipping. Accessed: 2024-07-26. 2024.

[86] P. Serra, P. Fadda, and G. Fancello. "Investigating the potential mitigating role of network design measures for reducing the environmental impact of maritime chains: The Mediterranean case". In: *Case Studies on Transport Policy* 8.2 (2020), pp. 263–280.

[87] A. Tokuşlu. "Analyzing the Energy Efficiency Design Index (EEDI) performance of a container ship". In: *International Journal of Environment and Geoinformatics* 7.2 (2020), pp. 114–119.

[88] G. DNV. *EEXI—Energy Efficiency Existing Ship Index*. 2022.

[89] DNV. *Maritime forecast to 2050*. Report. DNV, 2021.

[90] International Maritime Organization. *EEXI and CII - ship carbon intensity and rating system*. https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx. Accessed: 2024-07-26. 2024.

[91] B. Comer and F. Carvalho. "IMO's newly revised GHG strategy: what it means for shipping and the Paris Agreement". In: *The International Council on Clean Transportation* (2023).

[92] O. Merk, J. Hoffmann, and H. Haralambides. "Post-COVID-19 scenarios for the governance of maritime transport and ports". In: *Maritime Economics & Logistics* 24.4 (2022), pp. 673–685.

[93] C. Raucci, C. McKinlay, and A. Karan. *The Future of Maritime Fuels: What You Need to Know*. 2023.

[94] S. Speizer, J. Fuhrman, L. Aldrete Lopez, M. George, P. Kyle, S. Monteith, and H. McJeon. "Integrated assessment modeling of a zero-emissions global transportation sector". In: *Nature Communications* 15.1 (2024), p. 4439.

[95] D. P. Van Vuuren, M. Kok, P. L. Lucas, A. G. Prins, R. Alkemade, M. van den Berg, L. Bouwman, S. van der Esch, M. Jeuken, T. Kram, *et al.* "Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model". In: *Technological Forecasting and Social Change* 98 (2015), pp. 303–323.

[96] K. Calvin, P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R. Y. Cui, A. Di Vittorio, K. Dorheim, J. Edmonds, C. Hartin, M. Hejazi, R. Horowitz, G. Iyer, P. Kyle, S. H. Kim, R. Link, H. McJeon, S. J. Smith, A. Snyder, S. Waldhoff, and M. Wise. “GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems”. In: *Geoscientific Model Development* 12 (2019), pp. 677–698.

[97] E. De Cian, V. Bosetti, A. Sgobbi, and M. Tavoni. *The 2008 WITCH model: new model features and baseline*. 2009.

[98] Q.-T. Do, A. A. Levchenko, and C. Raddatz. “Comparative advantage, international trade, and fertility”. In: *Journal of Development Economics* 119 (2016), pp. 48–66.

[99] E. E. Leamer *et al. The Heckscher-Ohlin model in theory and practice*. 1995.

[100] H.-Y. Zhang, Q. Ji, and Y. Fan. “What drives the formation of global oil trade patterns?” In: *Energy Economics* 49 (2015), pp. 639–648.

[101] L. De Benedictis and D. Taglioni. *The gravity model in international trade*. Springer, 2011.

[102] J. M. Alston, C. A. Carter, R. Green, and D. Pick. “Whither Armington trade models?” In: *American Journal of Agricultural Economics* 72.2 (1990), pp. 455–467.

[103] J. Buongiorno. “Gravity models of forest products trade: Applications to forecasting and policy analysis”. In: *Forestry* 89.2 (2016), pp. 117–126.

[104] H.-Y. Zhang, W.-W. Xi, Q. Ji, and Q. Zhang. “Exploring the driving factors of global LNG trade flows using gravity modelling”. In: *Journal of Cleaner Production* 172 (2018), pp. 508–515.

[105] J. Ubøe, J. Andersson, K. Jörnsten, and S. P. Strandenes. “Modeling freight markets for coal”. In: *Maritime Economics & Logistics* 11 (2009), pp. 289–301.

[106] R. Adland, H. Jia, and S. P. Strandenes. “Are AIS-based trade volume estimates reliable? The case of crude oil exports”. In: *Maritime Policy & Management* 44.5 (2017), pp. 657–665.

[107] S. Babri, K. Jørnsten, and M. Viertel. “Application of gravity models with a fixed component in the international trade flows of coal, iron ore and crude oil”. In: *Maritime Economics & Logistics* 19 (2017), pp. 334–351.

[108] E. M. Kottou, T. A. Grubelich, and X. Wang. “Bilateral trade flow prediction models enhanced by wavelet and machine learning algorithms”. In: *2020 International Conference on Computational Science and Computational Intelligence (CSCI)*. IEEE. 2020, pp. 1510–1516.

[109] S. Circlaeys, C. Kanitkar, and D. Kumazawa. “Bilateral trade flow prediction”. In: *Unpublished manuscript, available for download at http://cs229. stanford. edu/proj2017/final-reports/5240224. pdf* (2017).

[110] J. Sun, Y. Suo, S. Park, T. Xu, Y. Liu, and W. Wang. “Analysis of Bilateral Trade Flow and Machine Learning Algorithms for GDP Forecasting.” In: *Engineering, Technology & Applied Science Research* 8.5 (2018).

[111] N. Minakawa, K. Izumi, and H. Sakaji. “Bilateral trade flow prediction by gravity-informed graph auto-encoder”. In: *2022 IEEE International Conference on Big Data (Big Data)*. IEEE. 2022, pp. 2327–2332.

[112] S. Tang, S. Xu, and J. Gao. “An optimal model based on multifactors for container throughput forecasting”. In: *KSCE Journal of Civil Engineering* 23.9 (2019), pp. 4124–4131.

[113] C.-C. Chou, C.-W. Chu, and G.-S. Liang. “A modified regression model for forecasting the volumes of Taiwan’s import containers”. In: *Mathematical and Computer Modelling* 47.9-10 (2008), pp. 797–807.

[114] Y. Huang, T. H. Rashidi, and L. Gardner. “Modelling the global maritime container network”. In: *Maritime Economics & Logistics* 20 (2018), pp. 400–420.

[115] D. Maxwell and Z. Zhu. “Natural gas prices, LNG transport costs, and the dynamics of LNG imports”. In: *Energy Economics* 33.2 (2011), pp. 217–226.

[116] E. Gómez-Herrera. “Comparing alternative methods to estimate gravity models of bilateral trade”. In: *Empirical economics* 44 (2013), pp. 1087–1111.

[117] J. S. Silva and S. Tenreyro. “The log of gravity”. In: *The Review of Economics and statistics* 88.4 (2006), pp. 641–658.

[118] B. Siliverstovs and D. Schumacher. “Estimating gravity equations: to log or not to log?” In: *Empirical Economics* 36 (2009), pp. 645–669.

[119] N. Michail, K. D. Melas, and D. Batzilis. “Container shipping trade and real GDP growth: A panel vector autoregressive approach”. In: *Nektarios A. Michail and Konstantinos D. Melas and Dimitris Batzilis,(2021)"Container shipping trade and real GDP growth: A panel vector autoregressive approach", Economics Bulletin* 41.2 (2021).

[120] Y. Li, X. Bai, Q. Wang, and Z. Ma. "A big data approach to cargo type prediction and its implications for oil trade estimation". In: *Transportation Research Part E: Logistics and Transportation Review* 165 (2022), p. 102831.

[121] BP. *BP Statistical Review of World Energy 2014-2021*. Accessed: 2024-07-30. 2021. url: `https://www.bp.com/statisticalreview`.

[122] World Bank. *GDP (current US$)*. Accessed: 2024-07-30. 2024. url: `https://data.worldbank.org/indicator/NY.GDP.MKTP.CD`.

[123] T.-C. Han and C.-M. Wang. "Shipping bunker cost risk assessment and management during the coronavirus oil shock". In: *Sustainability* 13.9 (2021), p. 4998.

[124] I. Wohl and J. Kennedy. "Neural network analysis of international trade". In: *US International Trade Commission: Washington, DC, USA* (2018).

[125] C. G. Thompson, R. S. Kim, A. M. Aloe, and B. J. Becker. "Extracting the variance inflation factor and other multicollinearity diagnostics from typical regression results". In: *Basic and Applied Social Psychology* 39.2 (2017), pp. 81–90.

[126] J. S. Kidwell and L. H. Brown. "Ridge regression as a technique for analyzing models with multicollinearity". In: *Journal of Marriage and the Family* (1982), pp. 287–299.

[127] Trade Map. *Trade Map - International Trade Statistics*. `https://www.trademap.org/Index.aspx`. 2024.

[128] Food and Agriculture Organization of the United Nations. *Land, Inputs and Sustainability: Land Use*. 2024. url: `https://www.fao.org/faostat/en/data/RL`.

[129] C. R. Services. *Global Shipping Data*. Data retrieved from Clarkson Research Services. Accessed: 2024-07-30. 2024. url: `https://www.clarksons.net/sin/global-shipping/`.

[130] K. Riahi, C. Bertram, D. Huppmann, J. Rogelj, V. Bosetti, A.-M. Cabardos, A. Deppermann, L. Drouet, S. Frank, O. Fricko, *et al.* "Cost and attainability of meeting stringent climate targets without overshoot". In: *Nature Climate Change* 11.12 (2021), pp. 1063–1069.

[131] J. Weyant. "Some contributions of integrated assessment models of global climate change". In: *Review of Environmental Economics and Policy* (2017).

[132] L. Van Beek, M. Hajer, P. Pelzer, D. van Vuuren, and C. Cassen. “Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970”. In: *Global Environmental Change* 65 (2020), p. 102191.

[133] M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, O. Edenhofer, T. F. Stocker, C. B. Field, K. L. Ebi, and P. R. Matschoss. “The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups”. In: *Climatic Change* 108 (2011), pp. 675–691.

[134] W. M. D. Team. *WITCH Model Documentation*. Accessed: 2024-07-30. 2024. url: `https://doc.witchmodel.org/`.

[135] I. A. M. C. (IAMC). *WITCH Model Resources*. Accessed: 2024-07-30. 2024. url: `https://www.iamconsortium.org/resources/model-resources/witch/`.

[136] S. Distances. *Online Distance Calculator*. Accessed: 2024-07-30. 2024. url: `https://sea-distances.org/`.

[137] B. C. O’Neill, E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. Van Ruijven, D. P. Van Vuuren, J. Birkmann, K. Kok, *et al.* “The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century”. In: *Global environmental change* 42 (2017), pp. 169–180.

[138] K. Samir and W. Lutz. “The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100”. In: *Global Environmental Change* 42 (2017), pp. 181–192.

[139] O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Strubegger, H. Valin, M. Amann, *et al.* “The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century”. In: *Global Environmental Change* 42 (2017), pp. 251–267.

[140] International Energy Agency. *Coal 2023*. Paris, 2023. url: `https://www.iea.org/reports/coal-2023`.

[141] P. Achakulwisut, P. Erickson, C. Guivarch, R. Schaeffer, E. Brutschin, and S. Pye. “Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions”. In: *Nature communications* 14.1 (2023), p. 5425.

[142] J. C. Refsgaard, J. P. van der Sluijs, A. L. Højberg, and P. A. Vanrolleghem. “Uncertainty in the environmental modelling process–a framework and guidance”. In: *Environmental modelling & software* 22.11 (2007), pp. 1543–1556.

[143] W. E. Walker, P. Harremoës, J. Rotmans, J. P. Van Der Sluijs, M. B. Van Asselt, P. Janssen, and M. P. Krayer von Krauss. “Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support”. In: *Integrated assessment* 4.1 (2003), pp. 5–17.

[144] J. Verschuur, E. Koks, and J. Hall. “Ports’ criticality in international trade and global supply-chains”. In: *Nature Communications* 13.1 (2022), p. 4351.

[145] J. Verschuur, E. E. Koks, and J. W. Hall. *Ports’ criticality in international trade and global supply-chains: Supplementary Information*. Supplementary Information. 2022. url: `https://doi.org/10.1038/s41467-022-32070-7`.

[146] J. Verschuur, E. E. Koks, and J. W. Hall. “Global economic impacts of COVID-19 lockdown measures stand out in high-frequency shipping data”. In: *PloS one* 16.4 (2021), e0248818.

[147] I. E. Agency. *Energy Technology Perspectives 2024*. Licence: CC BY 4.0. Paris: International Energy Agency, 2024. url: `https://www.iea.org/reports/energy-technology-perspectives-2024`.

[148] G. De Jong, A. Burgess, L. Tavasszy, R. Versteegh, M. de Bok, and N. Schmorak. “Distribution and modal split models for freight transport in The Netherlands”. In: *Proceedings of the 2011 European Transport Conference, Association for European Transport. On the generalized cost-demand elasticity of intermodal container transport*. 2011, pp. 1–18.

[149] W. Bank. “World development indicators online database”. In: *The World Bank Group* (2019). url: `https://data.worldbank.org/data-catalog/world-development-indicators`.

[150] T. Mayer and S. Zignago. *Notes on CEPII’s distances measures: The GeoDist database*. 2011.

[151] D. L. Hummels and G. Schaur. “Time as a trade barrier”. In: *American Economic Review* 103.7 (2013), pp. 2935–2959.

[152] G. Gaulier and S. Zignago. *Baci: international trade database at the product-level (the 1994-2007 version)*. 2010.

[153] M. Ben-Akiva and G. de Jong. “The aggregate-disaggregate-aggregate (ADA) freight model system”. In: *Freight transport modelling*. Emerald Group Publishing Limited, 2013, pp. 69–90.

[154] M. Ben-Akiva and M. Bierlaire. “Discrete choice methods and their applications to short term travel decisions”. In: *Handbook of transportation science*. Springer, 1999, pp. 5–33.

[155] E. W. Dijkstra. *A note on two problems in connexion with graphs*. 2022.

[156] O. Hall, M. F. A. Bustos, N. B. Olén, and T. Niedomysl. "Population centroids of the world administrative units from nighttime lights 1992-2013". In: *Scientific Data* 6.1 (2019), p. 235.

[157] L. Warszawski, K. Frieler, V. Huber, F. Piontek, O. Serdeczny, X. Zhang, Q. Tang, M. Pan, Y. Tang, Q. Tang, *et al.* "Center for international earth science information network—ciesin—columbia university.(2016). gridded population of the world, version 4 (gpwv4): Population density. palisades. ny: Nasa socioeconomic data and applications center (sedac). doi: 10. 7927/h4np22dq". In: *Atlas of Environmental Risks Facing China Under Climate Change* (2017), p. 228.

[158] M. Beenstock and A. Vergottis. *Econometric modelling of world shipping*. Springer Science & Business Media, 1993.

[159] T. Notteboom and J.-P. Rodrigue. "Containerisation, box logistics and global supply chains: The integration of ports and liner shipping networks". In: *Maritime economics & logistics* 10 (2008), pp. 152–174.

[160] T. E. ToolBox. *Higher Calorific Values of Common Fuels: Reference & Data*. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html. Accessed: March 06, 2025. 2003.

[161] Statista. *Annual fuel consumption by ships worldwide from 2019 to 2020, by fuel type (in million metric tons) [Graph]*. Retrieved March 06, 2025, from https://www.statista.com/statistics/1266963/amount-of-fuel-consumed-by-ships-worldwide-by-fuel-type/. Sept. 2021.

[162] Ø. Endresen, E. Sørgård, H. L. Behrens, P. O. Brett, and I. S. Isaksen. "A historical reconstruction of ships' fuel consumption and emissions". In: *Geophysical Research: Atmospheres* 112.D12 (2007).

[163] H. Lindstad and G. S. Eskeland. "Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution". In: *Transportation Research Part D: Transport and Environment* 41 (2015), pp. 244–256.

[164] United Nations Conference on Trade and Development. *Review of Maritime Transport 2004*. New York and Geneva: United Nations, 2004. url: https://unctad.org/system/files/official-document/rmt2004_en.pdf.

[165] United Nations Conference on Trade and Development. *Review of Maritime Transport 2011*. New York and Geneva: United Nations, 2011. url: https://unctad.org/system/files/official-document/rmt2011_en.pdf.

[166] H. Lindstad, B. E. Asbjørnslett, and A. H. Strømman. “The Importance of economies of scale for reductions in greenhouse gas emissions from shipping”. In: *Energy policy* 46 (2012), pp. 386–398.

[167] R. Adland and S. Koekebakker. “Ship valuation using cross-sectional sales data: A multivariate non-parametric approach”. In: *Maritime Economics & Logistics* 9 (2007), pp. 105–118.

[168] M. Furuichi and N. Otsuka. “Cost analysis of the Northern Sea Route (NSR) and the conventional route shipping”. In: *Proceedings of IAME 2013 conference*. Vol. 13. 2013.

[169] H. Lindstad and G. S. Eskeland. “Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution”. In: *Transportation Research Part D: Transport and Environment* 41 (2015), pp. 244–256.

[170] C. Research. *China Shipbuilding Weekly - Issue No. 767*. Accessed via TU Delft License. Jan. 2022. url: `http://www.clarksons.net`.

[171] C. Research. *World Shipyard Monitor - Volume 22, No. 10*. Accessed via TU Delft License. Oct. 2015. url: `http://www.clarksons.net`.

[172] C. Research. *World Shipyard Monitor - Volume 27, No. 7*. Accessed via TU Delft License. July 2020. url: `http://www.clarksons.net`.

[173] International Energy Agency. *International Shipping*. `https://www.iea.org/energy-system/transport/international-shipping`. Accessed: 2024-07-26.

[174] International Renewable Energy Agency (IRENA). *Decarbonising hard-to-abate sectors with renewables: Perspectives for the G7*. 2024.

[175] B. Comer and F. Carvalho. “IMO’s newly revised GHG strategy: what it means for shipping and the Paris Agreement”. In: *The International Council on Clean Transportation* (2023).

[176] Lloyd’s Register. *Summary Report: IMO Marine Environment Protection Committee (MEPC 83)*. Tech. rep. Briefing Note – Summary Report. London, UK: Lloyd’s Register, Apr. 2025. url: `https://maritime.lr.org/MEPC83-Ad`.

[177] T. Smith, A. Frosch, M. Fricaudet, P. Majidova, D. Oluteye, D. Baresic, and N. Rehmatulla. *An Overview of the Discussions from IMO’s 83rd Marine Environment Protection Committee*. Tech. rep. London, UK: UCL Energy Institute, Apr. 2025.

[178] International Energy Agency (IEA). *Tracking Clean Energy Progress 2023*. 2023. url: https://www.iea.org/reports/tracking-clean-energy-progress-2023.

[179] H. N. Psaraftis. “The future of maritime transport”. In: *Encyclopedia of Transportation*. Elsevier, 2020.

[180] P. A. Duong, B. R. Ryu, M. K. Song, H. V. Nguyen, D. Nam, and H. Kang. “Safety assessment of the ammonia bunkering process in the maritime sector: A review”. In: *Energies* 16.10 (2023), p. 4019.

[181] H. Naghash, D. Schott, and J. Pruyn. “Shifting waves of shipping: a review on global shipping projections and methodologies”. In: *Journal of Shipping and Trade* 9.1 (2024), pp. 1–43.

[182] P. Serra, P. Fadda, and G. Fancello. “Investigating the potential mitigating role of network design measures for reducing the environmental impact of maritime chains: The Mediterranean case”. In: *Case Studies on Transport Policy* 8.2 (2020), pp. 263–280.

[183] J. D. Ampah, A. A. Yusuf, S. Afrane, C. Jin, and H. Liu. “Reviewing two decades of cleaner alternative marine fuels: Towards IMO’s decarbonization of the maritime transport sector”. In: *Journal of Cleaner Production* 320 (2021), p. 128871. doi: 10.1016/j.jclepro.2021.128871.

[184] N. Gray, S. McDonagh, R. O’Shea, B. Smyth, and J. D. Murphy. “Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors”. In: *Advances in Applied Energy* 1 (2021), p. 100008. doi: 10.1016/j.adapen.2021.100008.

[185] L. C. Law, E. Mastorakos, and S. Evans. “Estimates of the Decarbonization Potential of Alternative Fuels for Shipping as a Function of Vessel Type, Cargo, and Voyage”. In: *Energies* 15 (2022), p. 7468. doi: 10.3390/en15207468.

[186] G. Mallouppas and E. A. Yfantis. “Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals”. In: *Journal of Marine Science and Engineering* 9 (2021), p. 415. doi: 10.3390/jmse9040415.

[187] Z. I. Rony, M. Mofijur, M. Hasan, M. Rasul, M. Jahirul, S. F. Ahmed, M. Kalam, I. A. Badruddin, T. Y. Khan, and P.-L. Show. “Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals”. In: *Fuel* 338 (2023), p. 127220. doi: 10.1016/j.fuel.2022.127220.

[188] S. Bouckaert, A. F. Pales, C. McGlade, U. Remme, B. Wanner, L. Varro, D. D’Ambrosio, and T. Spencer. *Net zero by 2050: A roadmap for the global energy sector*. 2021.

[189] R. A. Halim, L. Kirstein, O. Merk, and L. M. Martinez. “Decarbonization pathways for international maritime transport: A model-based policy impact assessment”. In: *Sustainability* 10.7 (2018), p. 2243.

[190] G. Castellanos, R. Roesch, A. Sloan, and D. Gielen. “A pathway to decarbonise the shipping sector by 2050”. In: *International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates* (2021).

[191] M. Traut, A. Larkin, K. Anderson, C. McGlade, M. Sharmina, and T. Smith. “CO2 abatement goals for international shipping”. In: *Climate policy* 18.8 (2018), pp. 1066–1075.

[192] D. Kramel, H. Muri, Y. Kim, R. Lonka, J. B. Nielsen, A. L. Ringvold, E. A. Bouman, S. Steen, and A. H. Strømman. “Global shipping emissions from a well-to-wake perspective: the MariTEAM model”. In: *Environmental science & technology* 55.22 (2021), pp. 15040–15050.

[193] A. S. Grzelakowski, J. Herdzik, and S. Skiba. “Maritime shipping decarbonization: Roadmap to meet zero-emission target in shipping as a link in the global supply chains”. In: *Energies* 15.17 (2022), p. 6150.

[194] Y. Zhao, F. Liu, Y. Zhang, Z. Wang, Z. Song, G. Zan, Z. Wang, H. Guo, H. Zhang, J. Zhu, *et al.* “Economic Assessment of Maritime Fuel Transformation for GHG Reduction in the International Shipping Sector.” In: *Sustainability* 16.23 (2024).

[195] H. Zhang, W. Chen, and W. Huang. “TIMES modelling of transport sector in China and USA: Comparisons from a decarbonization perspective”. In: *Applied Energy* 162 (2016), pp. 1505–1514.

[196] D. McCollum and C. Yang. “Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications”. In: *Energy Policy* 37.12 (2009), pp. 5580–5596.

[197] E. Müller-Casseres, A. Szklo, C. Fonte, F. Carvalho, J. Portugal-Pereira, L. B. Baptista, P. Maia, P. R. Rochedo, R. Draeger, and R. Schaeffer. “Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil”. In: *Iscience* 25.10 (2022).

[198] X. Pan, H. Wang, L. Wang, and W. Chen. “Decarbonization of China’s transportation sector: in light of national mitigation toward the Paris Agreement goals”. In: *Energy* 155 (2018), pp. 853–864.

[199] N. de Fournas and M. Wei. “Techno-economic assessment of renewable methanol from biomass gasification and PEM electrolysis for decarbonization of the maritime sector in California”. In: *Energy Conversion and Management* 257 (2022), p. 115440. doi: `10.1016/j.enconman.2022.115440`.

[200] B. Kanberoğlu, E. Turan, and G. Kökkülünk. “Decarbonization of Maritime Transportation: A Case Study for Turkish Ship Fleet”. In: *Journal of Marine Science and Application* 22 (2023), pp. 716–727. doi: 10.1007/s11804-023-00370-6.

[201] M. Prussi, N. Scarlat, M. Acciaro, and V. Kosmas. “Potential and limiting factors in the use of alternative fuels in the European maritime sector”. In: *Journal of Cleaner Production* 291 (2021), p. 125849. doi: 10.1016/j.jclepro.2021.125849.

[202] D. McCollum, V. Krey, P. Kolp, Y. Nagai, and K. Riahi. “Transport electrification: A key element for energy system transformation and climate stabilization”. In: *Climatic change* 123 (2014), pp. 651–664.

[203] R. C. Pietzcker, T. Longden, W. Chen, S. Fu, E. Kriegler, P. Kyle, and G. Luderer. “Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models”. In: *Energy* 64 (2014), pp. 95–108.

[204] B. Girod, D. P. Van Vuuren, M. Grahn, A. Kitous, S. H. Kim, and P. Kyle. “Climate impact of transportation A model comparison”. In: *Climatic change* 118 (2013), pp. 595–608.

[205] S. Yeh, G. S. Mishra, L. Fulton, P. Kyle, D. L. McCollum, J. Miller, P. Cazzola, and J. Teter. “Detailed assessment of global transport-energy models’ structures and projections”. In: *Transportation Research Part D: Transport and Environment* 55 (2017), pp. 294–309.

[206] I. De Blas, M. Mediavilla, I. Capellán-Pérez, and C. Duce. “The limits of transport decarbonization under the current growth paradigm”. In: *Energy Strategy Reviews* 32 (2020), p. 100543.

[207] B. Van der Zwaan, I. Keppo, and F. Johnsson. “How to decarbonize the transport sector?” In: *Energy policy* 61 (2013), pp. 562–573.

[208] E. C. Tan, T. R. Hawkins, U. Lee, L. Tao, P. A. Meyer, M. Wang, and T. Thompson. “Biofuel options for marine applications: technoeconomic and life-cycle analyses”. In: *Environmental Science & Technology* 55.11 (2021), pp. 7561–7570.

[209] E. Lindstad, G. S. Eskeland, A. Rialland, and A. Valland. “Decarbonizing maritime transport: The importance of engine technology and regulations for LNG to serve as a transition fuel”. In: *Sustainability* 12.21 (2020), p. 8793.

[210] J. R. Smith and E. Mastorakos. “A Systems-Level Study of Ammonia and Hydrogen for Maritime Transport”. In: *Maritime Transport Research* 5 (2023), p. 100099.

[211] E. Müller-Casseres, F. Leblanc, M. van den Berg, P. Fragkos, O. Dessens, H. Naghash, R. Draeger, T. L. Gallic, I. S. Tagomori, I. Tsiropoulos, J. Emmerling, L. B. Baptista, D. P. van Vuuren, A. Giannousakis, L. Drouet, J. Portugal-Pereira, H.-S. de Boer, N. Tsanakas, P. R. R. Rochedo, A. Szklo, and R. Schaeffer. "International shipping in a world below 2°C". In: *Nature Climate Change* 14 (2024), pp. 600–607. doi: 10.1038/s41558-024-01997-1.

[212] M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, O. Edenhofer, T. F. Stocker, C. B. Field, K. L. Ebi, and P. R. Matschoss. "The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups". In: *Climatic Change* 108 (2011), pp. 675–691.

[213] E. A. Bouman, E. Lindstad, A. I. Rialland, and A. H. Strømman. "State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–A review". In: *Transportation Research Part D: Transport and Environment* 52 (2017), pp. 408–421.

[214] D. Erdemir and I. Dincer. "A perspective on the use of ammonia as a clean fuel: Challenges and solutions." In: *International Journal of Energy Research* 45.4 (2021).

[215] D. Parris, K. Spinthiropoulos, K. Ragazou, A. Giovou, and C. Tsanaktsidis. "Methanol, a plugin marine fuel for green house gas reduction—a review". In: *Energies* 17.3 (2024), p. 605.

[216] E. Lindstad, B. Lagemann, A. Rialland, G. M. Gamlem, and A. Valland. "Reduction of maritime GHG emissions and the potential role of E-fuels". In: *Transportation Research Part D: Transport and Environment* 101 (2021), p. 103075.

[217] P. Havlík, H. Valin, A. Mosnier, S. Frank, P. Lauri, D. Leclere, A. Palazzo, M. Batka, E. Boere, A. Brouwer, *et al.* "GLOBIOM documentation". In: *International Institute for Applied Systems Analysis (IIASA)* (2018).

[218] R. M. Solow. "Neoclassical growth theory". In: *Handbook of macroeconomics* 1 (1999), pp. 637–667.

[219] I. E. Agency. *The Future of Hydrogen: Assumptions Annex*. Technical Report. Accessed: 2025-07-16. International Energy Agency, 2019. url: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf.

[220] J. M. M. Arcos and D. M. Santos. "The hydrogen color spectrum: techno-economic analysis of the available technologies for hydrogen production". In: *Gases* 3.1 (2023), pp. 25–46.

[221] P. Bains, S. Bennett, L. Collina, E. Connelly, C. Delmastro, S. Evangelopoulou, M. Fajardy, A. Gouy, M. Kotani, J. Le Marois, *et al.* “Global hydrogen review 2023”. In: *International Energy Agency: Paris, France* (2023).

[222] A. Bazzanella and F. Ausfelder. *Low carbon energy and feedstock for the European chemical industry: Technology Study*. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie eV, 2017.

[223] B. Helgeson and J. Peter. “The role of electricity in decarbonizing European road transport–Development and assessment of an integrated multi-sectoral model”. In: *Applied Energy* 262 (2020), p. 114365.

[224] R. O. Cebolla, F. Dolci, and E. Weidner. *Assessment of hydrogen delivery options: feasibility of transport of green hydrogen within Europe*. 2022.

[225] M. Wang, M. A. Khan, I. Mohsin, J. Wicks, A. H. Ip, K. Z. Sumon, C.-T. Dinh, E. H. Sargent, I. D. Gates, and M. G. Kibria. “Can sustainable ammonia synthesis pathways compete with fossil-fuel based Haber–Bosch processes?” In: *Energy & Environmental Science* 14.5 (2021), pp. 2535–2548.

[226] S. Brynolf, M. Taljegard, M. Grahn, and J. Hansson. “Electrofuels for the transport sector: A review of production costs”. In: *Renewable and Sustainable Energy Reviews* 81 (2018), pp. 1887–1905.

[227] M. Pérez-Fortes, J. C. Schöneberger, A. Boulamanti, and E. Tzimas. “Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment”. In: *Applied energy* 161 (2016), pp. 718–732.

[228] K. Schoots, F. Ferioli, G. Kramer, and B. Van der Zwaan. “Learning curves for hydrogen production technology: An assessment of observed cost reductions”. In: *International Journal of Hydrogen Energy* 33.11 (2008), pp. 2630–2645.

[229] G. Glenk, P. Holler, and S. Reichelstein. “Advances in power-to-gas technologies: cost and conversion efficiency”. In: *Energy & Environmental Science* 16.12 (2023), pp. 6058–6070.

[230] H. Naghash, J. Pruyn, and D. Schott. *Estimating Energy Requirements in Maritime Shipping: From Ton–Mile Demand to Fuel Consumption*. Preprint, Delft University of Technology. Available on ResearchGate. May 2025. doi: `10.13140/RG.2.2.12104.84484`. url: `https://www.researchgate.net/publication/391899206_Estimating_Energy_Requirements_in_Maritime_Shipping_From_Ton-Mile_Demand_to_Fuel_Consumption`.

[231] Mærsk Mc–Kinney Møller Center for Zero Carbon Shipping. *Calculate Total Cost of Ownership (TCO) for Decarbonization of Vessels*. Accessed: 2025-05-15. Nov. 2021. url: `https://www.zerocarbonshipping.com/publications/calculate-total-cost-of-ownership-tco-for-decarbonization-of-vessels`.

[232] H. Naghash, D. Schott, and J. Pruyn. "Evolving shipping activity in climate scenarios: Coupling econometrics with Integrated Assessment Model". In: *Ocean Engineering* 322 (2025), p. 120516.

[233] E. Byers, V. Krey, E. Kriegler, K. Riahi, R. Schaeffer, J. Kikstra, R. Lamboll, Z. Nicholls, M. Sandstad, C. Smith, K. van der Wijst, A. Al Khourdajie, F. Lecocq, J. Portugal-Pereira, Y. Saheb, A. Stromann, H. Winkler, C. Auer, E. Brutschin, M. Gidden, P. Hackstock, M. Harmsen, D. Huppmann, P. Kolp, C. Lepault, J. Lewis, G. Marangoni, E. Müller-Casseres, R. Skeie, M. Werning, K. Calvin, P. Forster, C. Guivarch, T. Hasegawa, M. Meinshausen, G. Peters, J. Rogelj, B. Samset, J. Steinberger, M. Tavoni, and D. van Vuuren. *AR6 Scenarios Database*. Version 1.1. Accessed: 2024. 2022. url: `https://doi.org/10.5281/zenodo.5886911`.

[234] International Energy Agency. *World Energy Investment 2025*. Licence: CC BY 4.0. Paris: IEA, 2025. url: `https://www.iea.org/reports/world-energy-investment-2025`.

[235] M. Sharmina, O. Y. Edelenbosch, C. Wilson, R. Freeman, D. Gernaat, P. Gilbert, A. Larkin, E. Littleton, M. Traut, D. P. van Vuuren, *et al.* "Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2 C". In: *Climate Policy* 21.4 (2021), pp. 455–474.

[236] D. Baresic, V. Prakash, J. Stewart, P. Langer, T. Smith, M. Fricaudet, and N. Rehmatulla. *Climate Action in Shipping: Progress towards shipping's 2030 breakthrough*. Tech. rep. UCL, 2025.

[237] J.-P. Rodrigue. *The geography of transport systems*. Routledge, 2020.

[238] **Naghash, Hesam**, D. Schott, and J. Pruyn. "**Evolving shipping activity in climate scenarios: Coupling econometrics with Integrated Assessment Model**". In: *Ocean Engineering* 322 (2025), p. 120516.

[239] N. Pocitarenco, O. Aneziris, I. Koromila, Z. Nivolianitou, M. Gerbec, V. Maras, and E. Salzano. "A Systematic Literature Review on Safety of Ammonia as a Marine Fuel". In: *Chemical Engineering Transactions* 116 (2025), pp. 733–738.

[240] M. Pfennig, D. Böttger, B. Häckner, D. Geiger, C. Zink, A. Bisevic, and L. Jansen. “Global GIS-based potential analysis and cost assessment of Power-to-X fuels in 2050”. In: *Applied Energy* 347 (2023), p. 121289.

[241] IEA. *Energy Technology Perspectives 2024*. IEA, Paris. 2024. url: `https://www.iea.org/reports/energy-technology-perspectives-2024`.

[242] U. EIA. “World oil transit chokepoints”. In: *US Energy Information Administration* (2017).

[243] U. EIA. “World oil transit chokepoints”. In: *US Energy Information Administration* (2024).

[244] L. M. Alexander. “The role of choke points in the ocean context”. In: *GeoJournal* 26 (1992), pp. 503–509.

[245] IMO. *Fourth IMO GHG study 2020*. Journal Article. 2020.

[246] **Naghash, Hesam**, D. Schott, and J. Pruyn. “**Shifting waves of shipping: a review on global shipping projections and methodologies**”. In: *Journal of Shipping and Trade* 9.1 (2024), pp. 1–43.

A

LITERATURE REVIEW

Table A.1.: Details of MCDA ratings.

Average Rate	Method	Study	Dimensionality	Technology Range	Integration Scope	Geographical scope	Scenario Evaluation	Total score
8.89	Integrated modeling	[18]	1.33	2	2	2	2	9.33
		[42]	1.33	2	2	2	2	9.33
		[19]	2	2	2	0	2	8
		[4]	0.66	2	2	2	2	8.66
		[4]	1.33	2	2	2	2	9.33
		[35]	0.66	2	2	2	2	8.66
7	Sectoral modeling	[46]	1.33	2	0	0	2	5.33
		[41]	1.33	2	0	2	2	7.33
		[34]	1.33	2	0	2	2	7.33
		[27]	1.33	2	0	2	2	7.33
		[47]	0.66	2	0	2	2	6.66
		[29]	2	2	0	2	2	8
		[43]	2	2	0	2	2	8
		[33]	1.33	2	0	2	2	7.33
		[49]	1.33	0	0	2	2	5.33
		[48]	1.33	2	0	2	2	7.33
7	Regression Analysis	[45]	0.66	2	0	2	2	6.66
		[44]	1.33	2	0	2	2	7.33
5.43	Life-cycle assessment	[50]	0.66	2	0	2	0	4.66
		[10]	1.33	2	0	2	2	7.33
		[31]	0.66	0	0	2	2	4.66
		[52]	0.66	2	0	2	0	4.66
		[53]	0.66	0	0	2	2	4.66
		[62]	0.66	2	0	2	2	6.66
7.16	Undisclosed (Reports)	[36]	1.33	2	0	2	2	7.33
		[3]	1.33	2	0	2	2	7.33
		[54]	1.33	2	0	2	2	7.33
		[55]	0.66	2	0	2	2	6.66

B

MODEL EXTRA INFORMATION

B.1. ECONOMETRIC DEMAND MODEL

Table B.1.: Table of econometric models specifics.

Category	Econometric model	Determinant variables	Estimation method	Data source and span
Energy	Augmented & disaggregated gravity model	GDP, Consumption, Production, Distance, Fuel price	RIDGE	bpstats 2014-2021
Non-energy Major bulk	Disaggregated gravity model	GDP, Distance, Fuel price	OLS	Trademap 2015-2021
Minor bulk and containerized	Gravity application based model & allocation distribution	GDP, Fuel price	OLS	Clarksons 2002-2021

Table B.2.: Variance Inflation Factors (VIF) for Different Variables Across Models

Variable	**Coal (VIF)**	**Gas (VIF)**	**Crude Oil (VIF)**	**Petroleum Product (VIF)**
Production_x	60.79	48.83	4.28	2.48
Consumption_i	48.77	57.83	25.68	22.73
Production_i	47.61	34.05	2.04	2.21
Consumption_x	54.15	73.10	19.72	26.14
fprice	8.54	7.26	9.11	9.56
Distance	4.78	5.49	4.91	5.09
GDP_i	3.33	8.80	15.51	14.07
GDP_x	2.47	8.20	11.10	14.99

Table B.3.: Number of Observations Used for Each Cargo Model.

Cargo Type	**Grains**	**Iron Ore**	**Coal**	**LNG**	**Oil & Products**	**Containerized**	**Minor bulk**
Observations	1292	1408	216	284	720	680	20

Table B.4.: Variance Inflation Factors (VIF) for Iron Ore and Grain Models

Variable	**Iron Ore (VIF)**	**Grain (VIF)**
GDPX	1.84	1.74
GDPI	1.67	1.68
DISTANCE	5.84	5.62
FPRICE	5.74	5.31

Table B.5.: Validation metrics for econometric models

Model	$\mathbf{R^2}$	**MSE**	**RMSE**	**MAE**
Oil and Petroleum Products	0.859	0.289	0.538	0.401
Coal	0.792	0.359	0.599	0.475
LNG	0.818	0.240	0.490	0.356
Containerized Cargo	0.987	0.017	0.132	0.109
Iron Ore	0.939	0.081	0.284	0.203
Grains	0.878	0.109	0.331	0.234

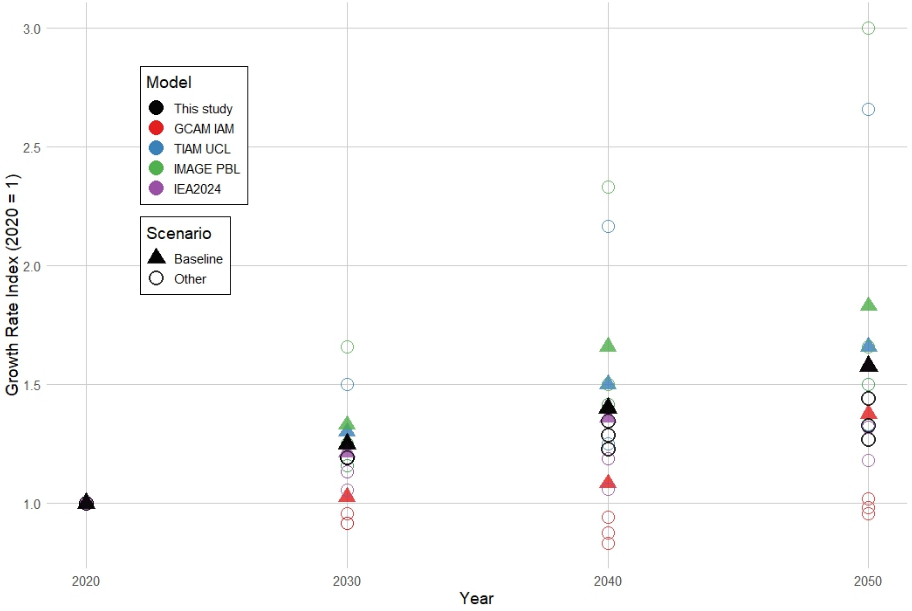
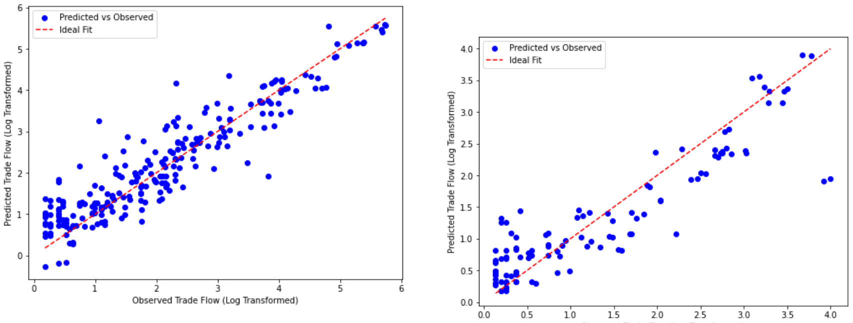
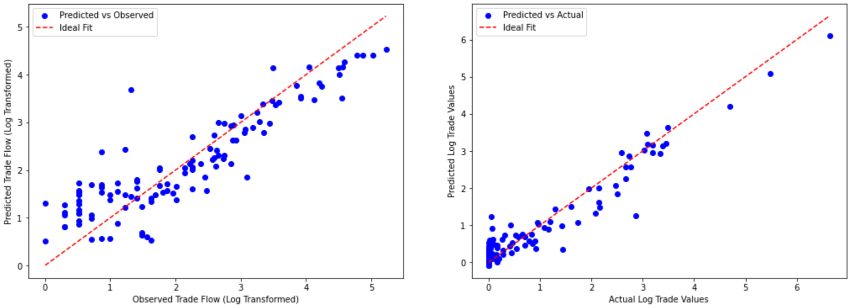


Figure B.1.: Comparison of results with those of similar works predicting future global shipping demand. References for data: GCAM IAM [94], TIAM UCL [42], IMAGE PBL [18], IEA2024 [241].



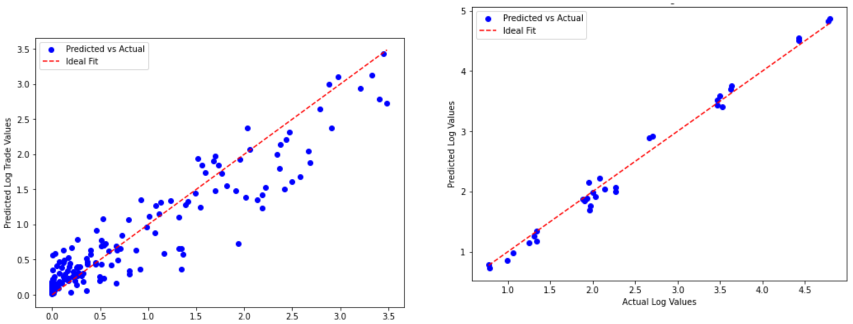
(a) Predicted trade flows vs actual observed flows for oil and petroleum products

(b) Predicted trade flows vs actual observed flows for LNG



(c) Predicted trade flows vs actual observed flows for coal

(d) Predicted trade flows vs actual observed flows for iron ore



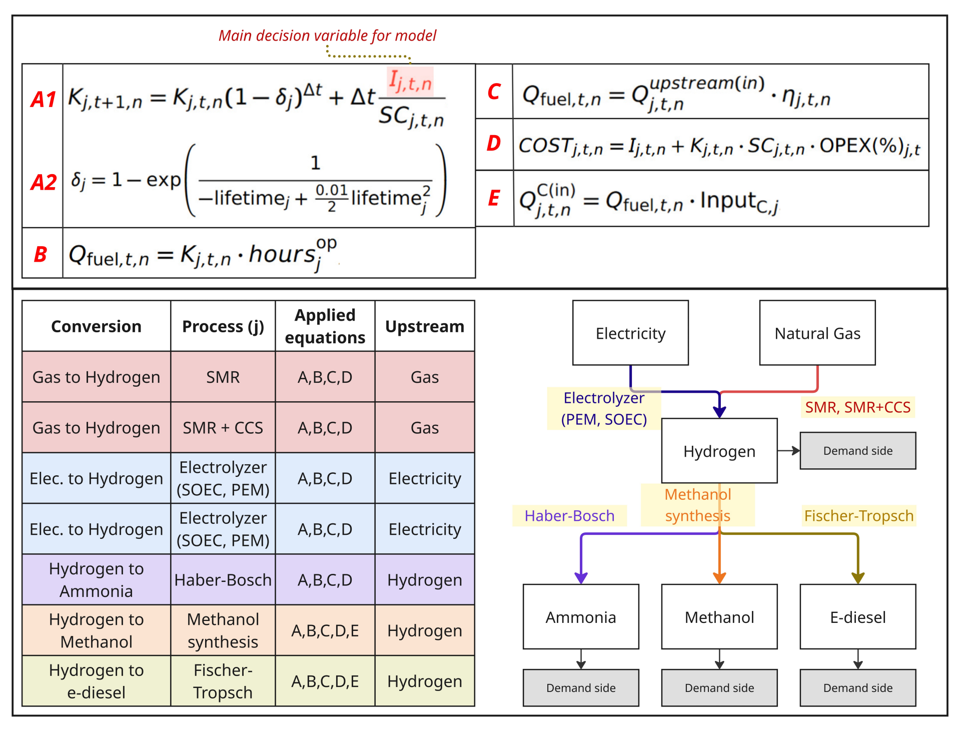
(e) Predicted trade flows vs actual observed flows for whole grains

(f) Predicted trade flows vs actual observed flows for Containerized cargo

Figure B.2.: Validation results for econometric models. Each panel shows the actual versus predicted values for a specific model or cargo category. The 2022 and 2023 data are used for validation.

B.2. FUEL SUPPLY MODULE

B.2.1. ADDITIONAL EQUATIONS



Main decision variable for model

A1 $K_{j,t+1,n} = K_{j,t,n}(1-\delta_j)^{\Delta t} + \Delta t \frac{I_{j,t,n}}{SC_{j,t,n}}$

A2 $\delta_j = 1 - \exp\left(\frac{1}{-\text{lifetime}_j + \frac{0.01}{2}\text{lifetime}_j^2}\right)$

B $Q_{\text{fuel},t,n} = K_{j,t,n} \cdot hours_j^{op}$

C $Q_{\text{fuel},t,n} = Q_{j,t,n}^{upstream(in)} \cdot \eta_{j,t,n}$

D $COST_{j,t,n} = I_{j,t,n} + K_{j,t,n} \cdot SC_{j,t,n} \cdot \text{OPEX}(\%)_{j,t}$

E $Q_{j,t,n}^{C(in)} = Q_{\text{fuel},t,n} \cdot \text{Input}_{C,j}$

Conversion	Process (j)	Applied equations	Upstream
Gas to Hydrogen	SMR	A,B,C,D	Gas
Gas to Hydrogen	SMR + CCS	A,B,C,D	Gas
Elec. to Hydrogen	Electrolyzer (SOEC, PEM)	A,B,C,D	Electricity
Elec. to Hydrogen	Electrolyzer (SOEC, PEM)	A,B,C,D	Electricity
Hydrogen to Ammonia	Haber-Bosch	A,B,C,D	Hydrogen
Hydrogen to Methanol	Methanol synthesis	A,B,C,D,E	Hydrogen
Hydrogen to e-diesel	Fischer-Tropsch	A,B,C,D,E	Hydrogen

Figure B.3.: Detailed information on power-to-X fuel production equations for hydrogen, ammonia, methanol, and e-diesel

Table B.6.: Model parameters and variables used in the fuel production equations.

Parameter / Variable	**Definition**	**Units**
Q_{fuel}	Amount of produced fuel	TWh
K	Installed capacity	TW
$hours^{\text{op}}$	Operational work hours of plant	Hours/year
$Q^{\text{upstream(in)}}$	Amount of upstream energy	TWh
η	Conversion process efficiency	%
$Q^{\text{C(in)}}$	Required carbon by the process	MtonC
Input_{C}	Specific carbon requirement of the process	kgC/kWh
COST	Total cost incurred by process	T$
I	Investment in the process	T$
SC	Specific investment cost	$/Wh
OPEX	OPEX related to maintenance of the plant	% of CAPEX
$Lifetime$	Lifetime of the plant	Years

Table B.7.: MEPC Net-zero framework. Annual GFI reduction factors (in percentage) for the target annual GFI relative to the GFI reference value. The table shows the detailed GHG Fuel Intensity (GFI) reduction thresholds for each carbon levy tier: vessels that meet or exceed the direct-compliance target incur no levy, those achieving reductions between the base and direct targets are charged the Tier 1 rate, and vessels below the base target pay the Tier 2 rate.

Year	**Base target**	**Direct compliance target**
2028	4%	17%
2029	6%	19%
2030	8%	21.0%
2031	12.4%	25.4%
2032	16.8%	29.8%
2033	21.2%	34.2%
2034	25.6%	38.6%
2035	30.0%	43%
2040	65%	TBD

B.2.2. INTER-MODEL LINKAGES

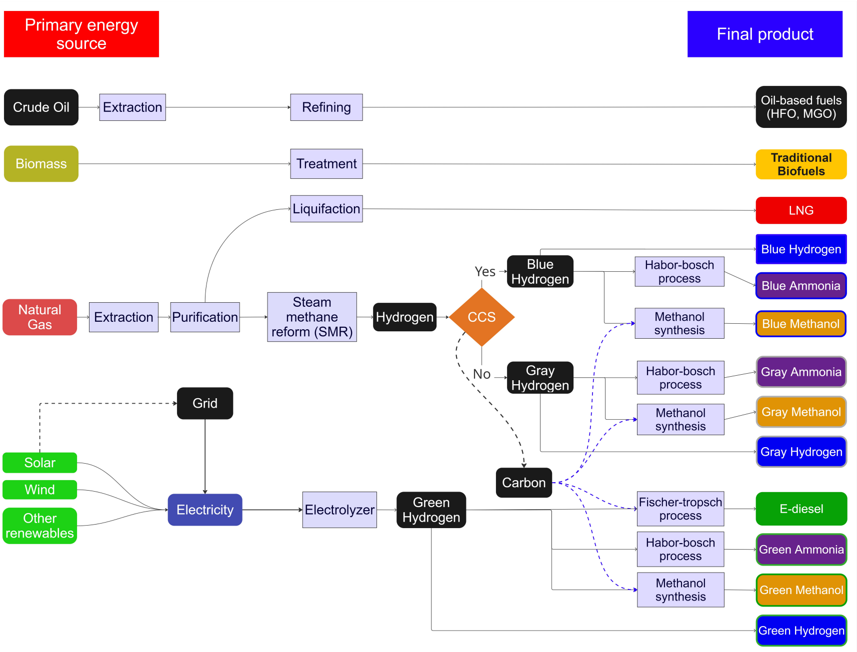


Figure B.4.: Fuel modeling pathway. Flowchart of fuel modeling pathways. Starting from primary energy sources, going through processes, and obtaining final products.

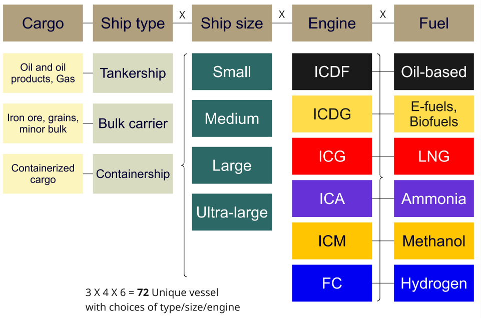


Figure B.5.: Internal connectivity of maritime module. Connection of cargo transport demand to specific ship types and sizes. Engine options for each vessel, and corresponding fuels.

C

SPATIAL AND STRUCTURAL MAPPINGS

Table C.1.: Passability of chokepoints and canals by ship type and size. References: [241–244]

Chokepoint/Canal	Container Ships (TEU)	Bulk Carriers (DWT)	Oil Tankers (DWT)
Strait of Hormuz	No restrictions; all sizes (up to 24,000+ TEU)	No restrictions; all sizes (up to 400,000 DWT)	No restrictions; ULCCs (up to 500,000 DWT) can pass
Strait of Malacca	Limited to vessels with draft ≤23 m; ∼20,000 TEU max	Capesize restricted; limited to ∼150,000 DWT	Limited to Suezmax (∼200,000 DWT); VLCCs with lightering
Suez Canal	Allows New Panamax (∼15,000 TEU) and most ULCVs	Capesize allowed with constraints; VLOCs restricted (∼200,000 DWT max)	Limited to Suezmax (∼200,000 DWT)
Panama Canal	Limited to New Panamax (≤15,000 TEU)	Capesize restricted; Panamax (∼80,000 DWT) and smaller allowed	Limited to Aframax (∼120,000 DWT) and smaller
Bab-el-Mandeb Strait	No restrictions; all sizes (up to 24,000+ TEU)	No restrictions; all sizes (up to 400,000 DWT)	No restrictions; ULCCs (up to 500,000 DWT) can pass
Danish Straits	Limited to vessels with draft ≤15 m; ∼5,000 TEU max	Panamax (∼80,000 DWT) and smaller allowed	Limited to Aframax (∼120,000 DWT) and smaller
Turkish Straits	Limited to vessels with draft ≤15 m; ∼5,000 TEU max	Panamax (∼80,000 DWT) and smaller allowed	Limited to Aframax (∼120,000 DWT) and smaller
Cape of Good Hope	No restrictions; all sizes (up to 24,000+ TEU)	No restrictions; all sizes (up to 400,000 DWT)	No restrictions; ULCCs (up to 500,000 DWT) can pass

Table C.2.: Distribution of ship types, capacities, and categories. Reference: [245]

Vessel Type	Vessel Capacity	Size Category	Distribution of Ships (Capacity)
Containership (TEU)	<3k	Feeder	19%
	3–6k	Intermediate	23%
	6–8k	Intermediate	9%
	8–12k	Neo-Panamax	27%
	12–15k	Neo-Panamax	14%
	>15k	Post-Panamax	9%
Bulker (DWT)	<40k	Handysize	12%
	40–60k	Handymax	24%
	60–80k	Panamax	25%
	>80k	Capesize	39%
Tanker (DWT)	<55k	Handysize	22%
	55–85k	Panamax	6%
	85–125k	Aframax	19%
	125–200k	Suezmax	15%
	>200k	UL/VLCC	39%

Table C.3.: Regions, representations, and proxy ports used in Chapter 3.

Region code	Represented region(s)	Proxy port(s)
CANADA	Canada	Montreal (E), Vancouver (W)
EUROPE	Western Europe	Rotterdam
JPNKOR	Japan, Korea	Chiba
MEXICO	Mexico	Manzanillo
OCEANIA	Australia, New Zealand	Brisbane
USA	United States of America	Galveston (E), Los Angeles (W)
BRAZIL	Brazil	Santos
INDIA	India	Mumbai
INDONESIA	Indonesia	Tanjung Priok
LACA	Latin America & Caribbean	Panama
MENA	Middle East & North Africa	Jebel Ali
SA	South Africa	Durban
SASIA	South Asia (Afghanistan, Pakistan)	Karachi
SEASIA	South East Asia	Singapore
SSA	Sub-Saharan Africa	Mombasa (E), Lagos (W)
TE	Eastern Europe incl. Russia	Novorossiysk (W), Vostochnyy (E)

D

EXTENDED RESULTS

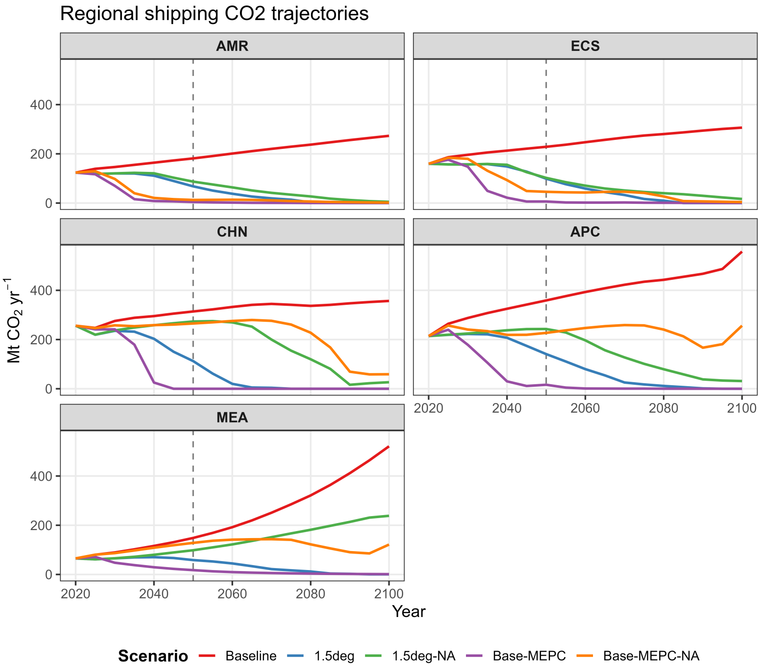


Figure D.1.: Shipping emission of macro-regions. Related to Chapter 6.

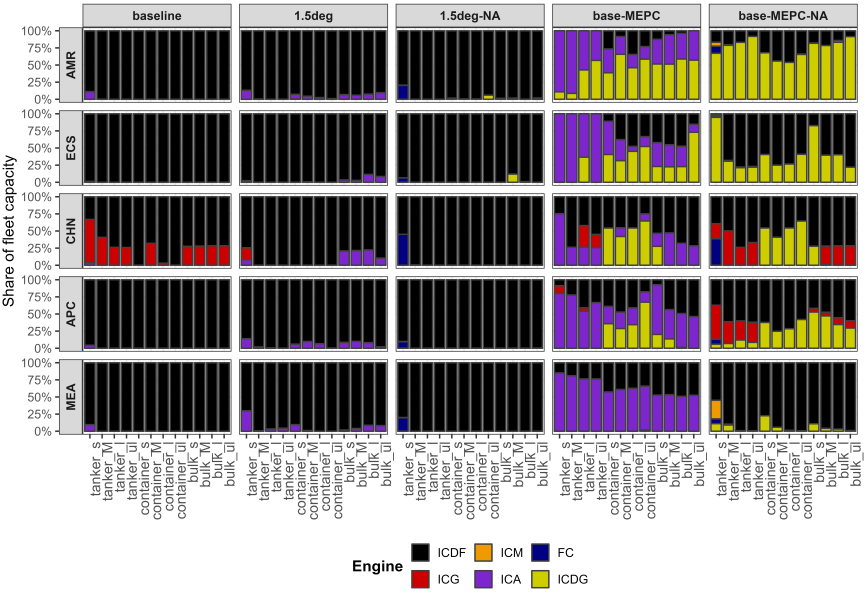


Figure D.2.: Fleet composition for 2030. Related to Chapter 6.

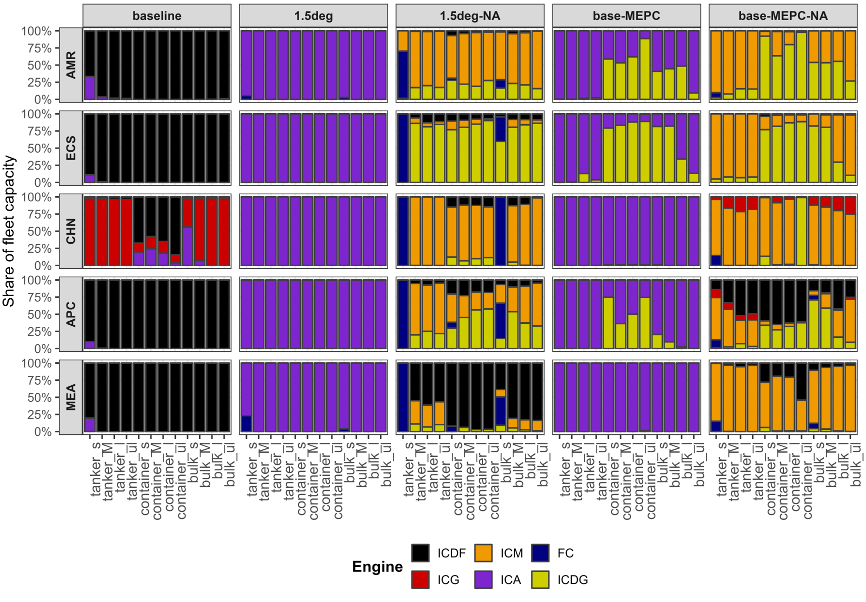


Figure D.3.: Fleet composition for 2100. Related to Chapter 6.

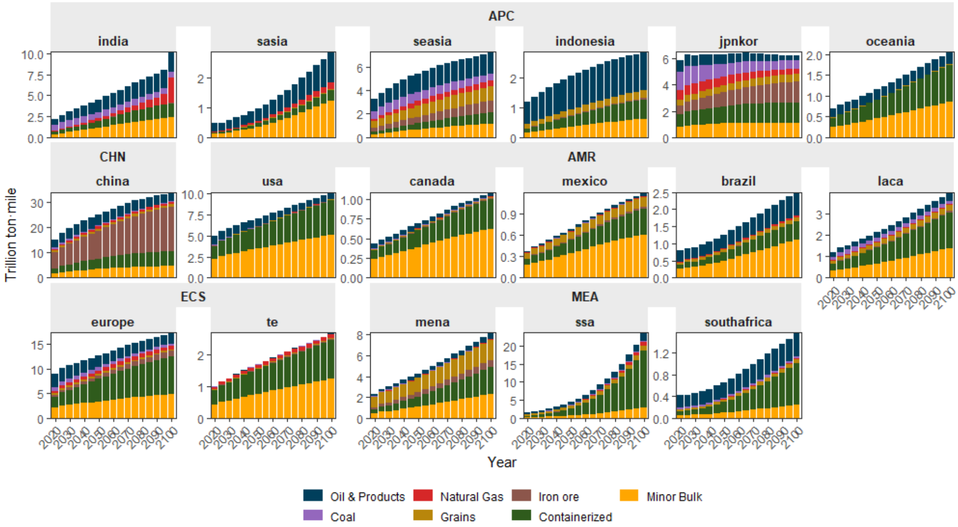


Figure D.4.: Detailed shipping demand of regions in Baseline scenarios. Related to Chapter 6.

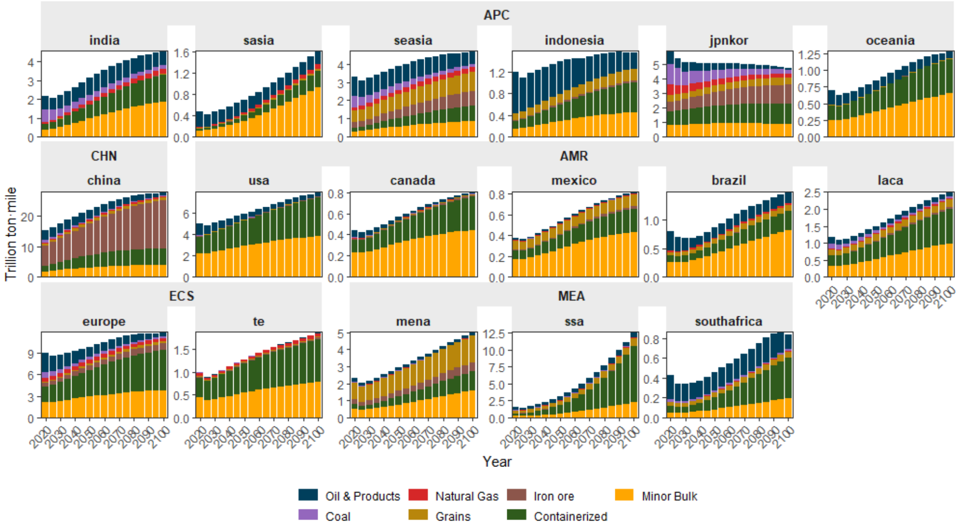


Figure D.5.: Detailed shipping demand of regions in 1.5°C-based scenarios. Related to Chapter 6.

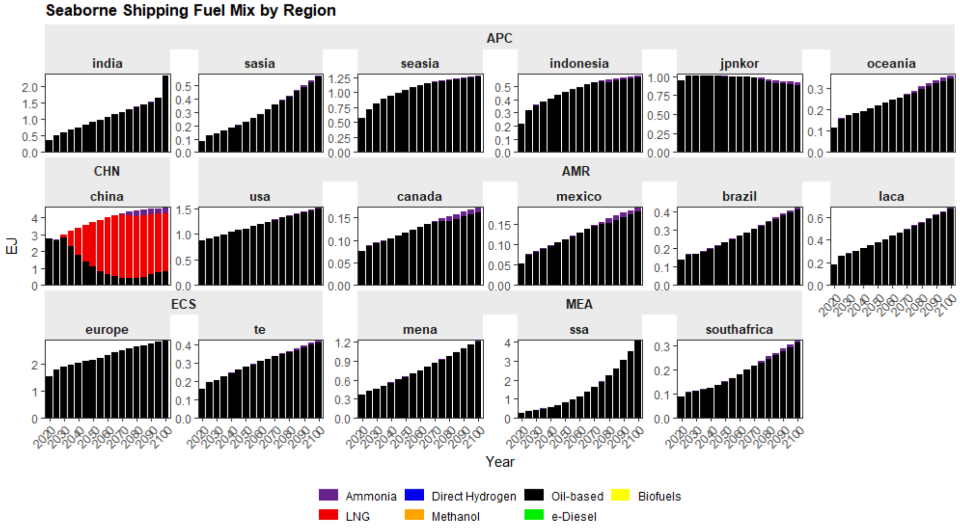


Figure D.6.: Detailed maritime shipping fuel mix of sub-regions in Baseline scenario. Related to Chapter 6.

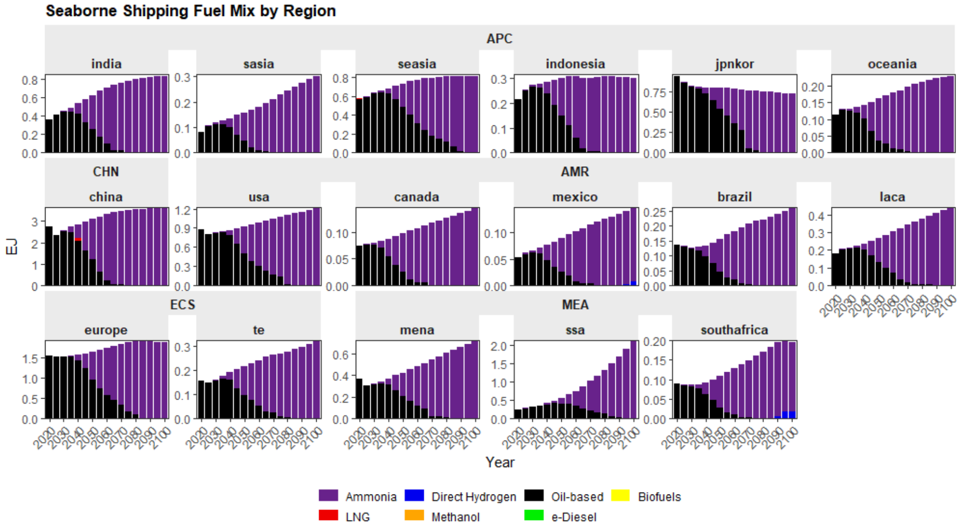


Figure D.7.: Detailed maritime shipping fuel mix of sub-regions in 1.5°C scenario. Related to Chapter 6.

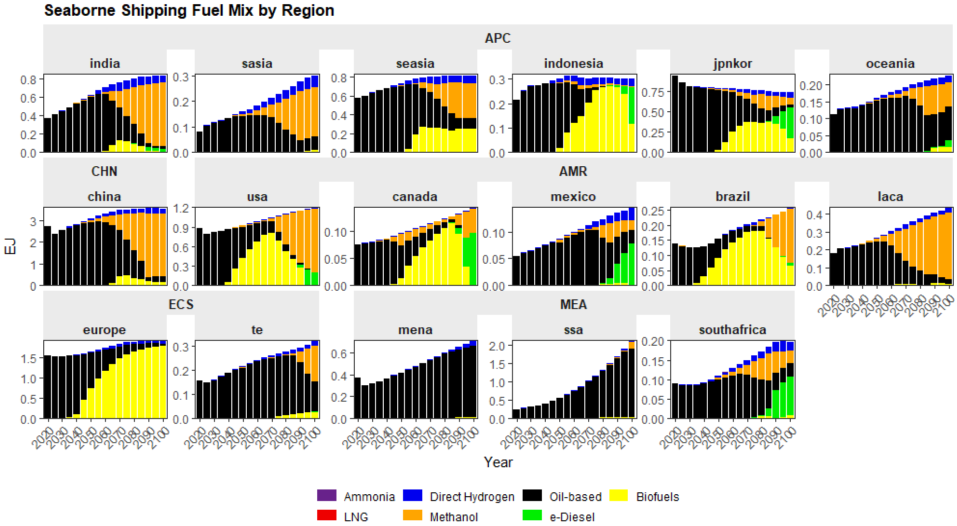


Figure D.8.: Detailed maritime shipping fuel mix of sub-regions in 1.5°C-NA scenario. Related to Chapter 6.

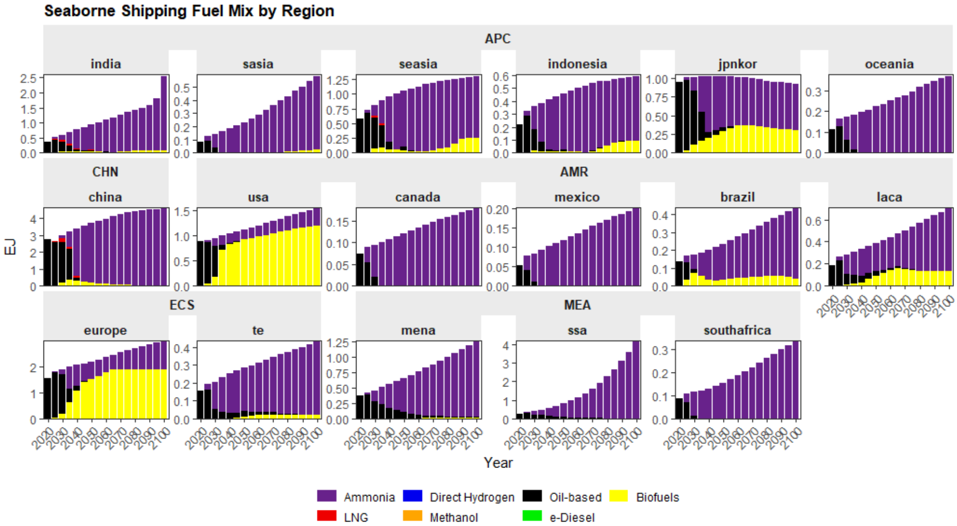


Figure D.9.: Detailed maritime shipping fuel mix of sub-regions in Base-MEPC scenario. Related to Chapter 6.

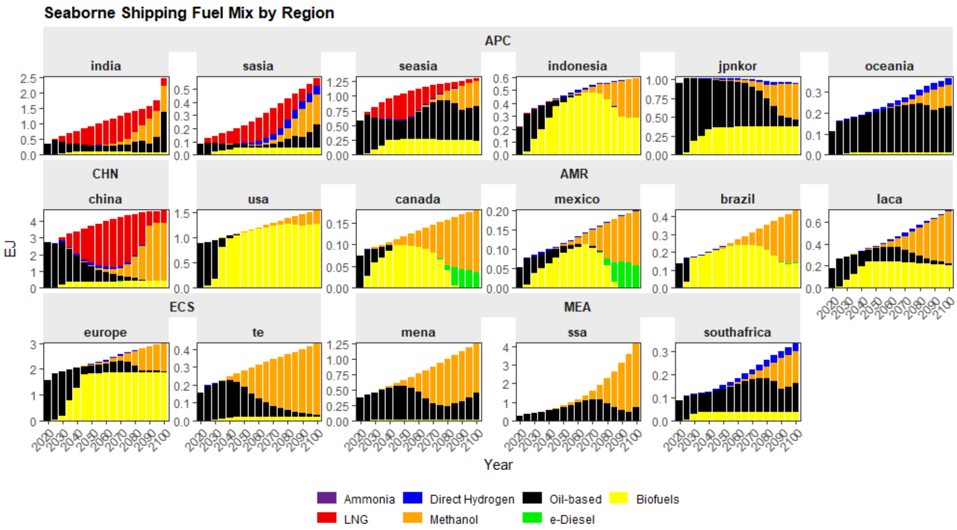


Figure D.10.: Detailed maritime shipping fuel mix of sub-regions in Base-MEPC-NA scenario. Related to Chapter 6.

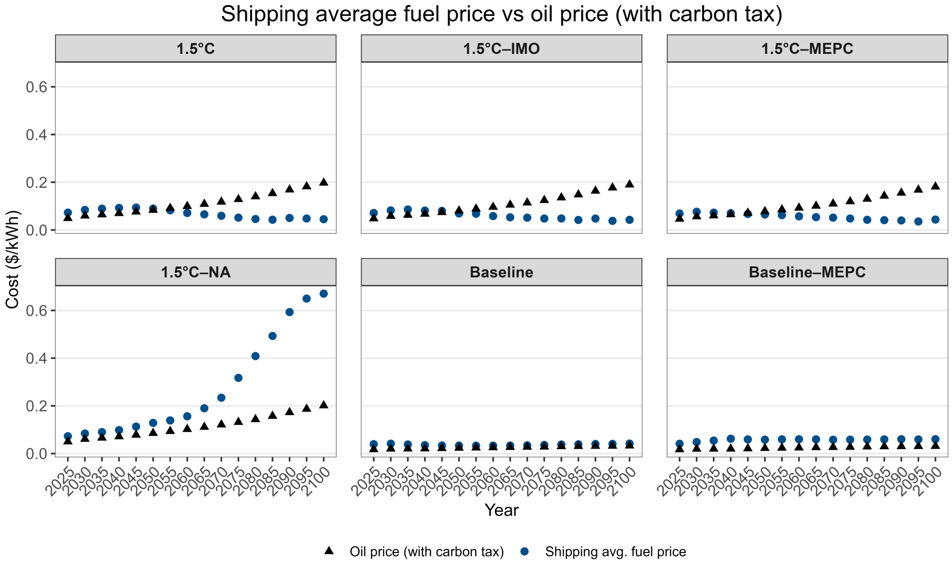


Figure D.11.: Shipping average fuel price vs oil price. Scenarios are related to Chapter 5.

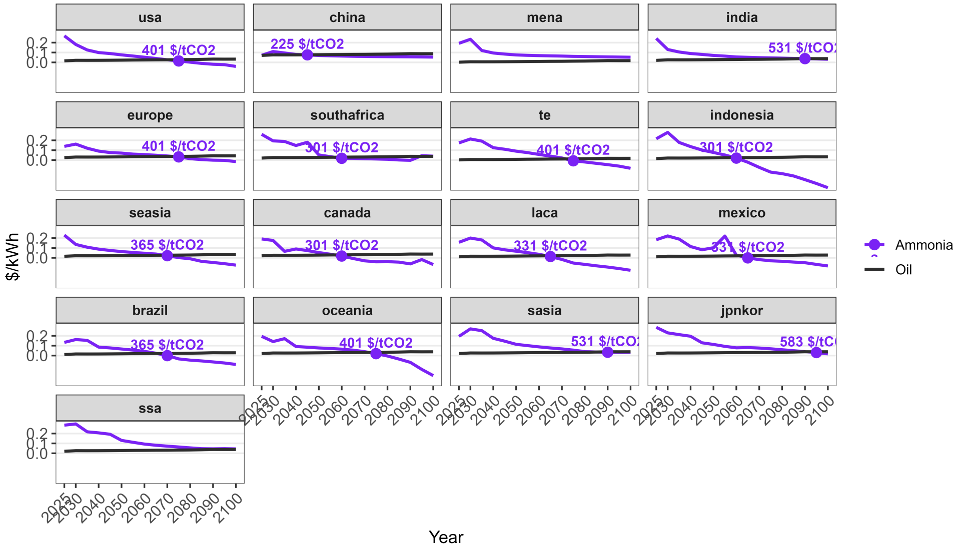


Figure D.12.: Ammonia and oil break-even cost point across regions; 1.5 °C scenario.

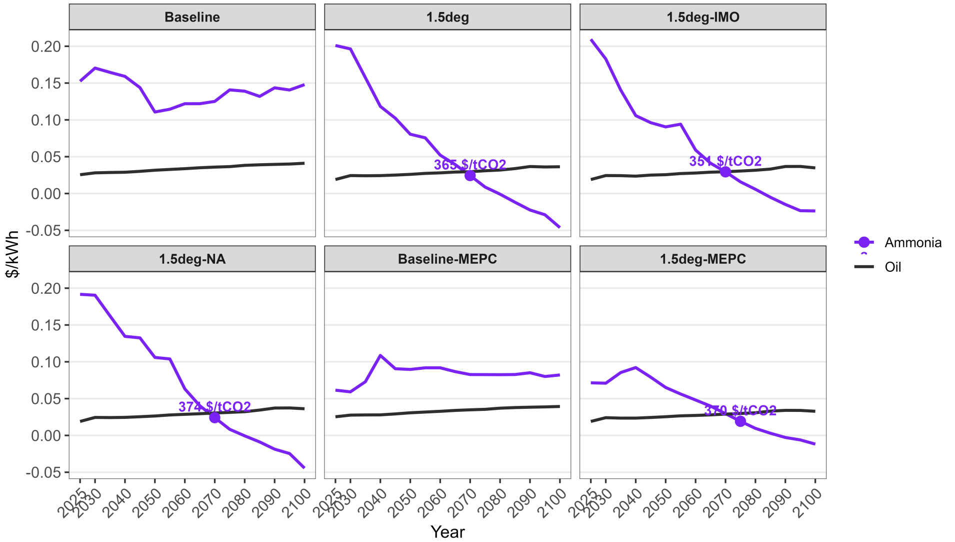


Figure D.13.: Ammonia and oil break-even cost point across scenarios; averaged over regions. Scenarios are related to Chapter 5.

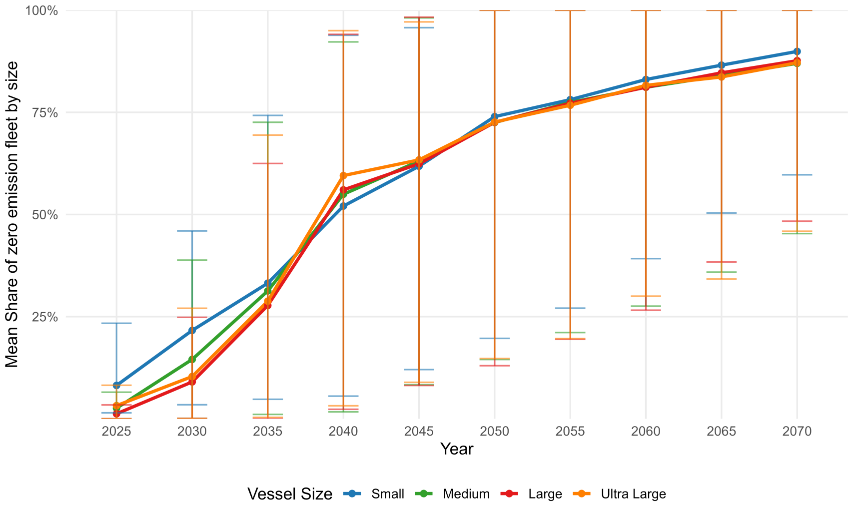


Figure D.14.: Mean share of zero-emission fleet by size. Averaged over scenarios; small-sized vessels before 2035 and after 2050 dominate the transition due to their higher specific fuel consumption and relevance for decarbonization. In the mid-term, Ultra-large vessels take the lead due to their high transport and working loads.

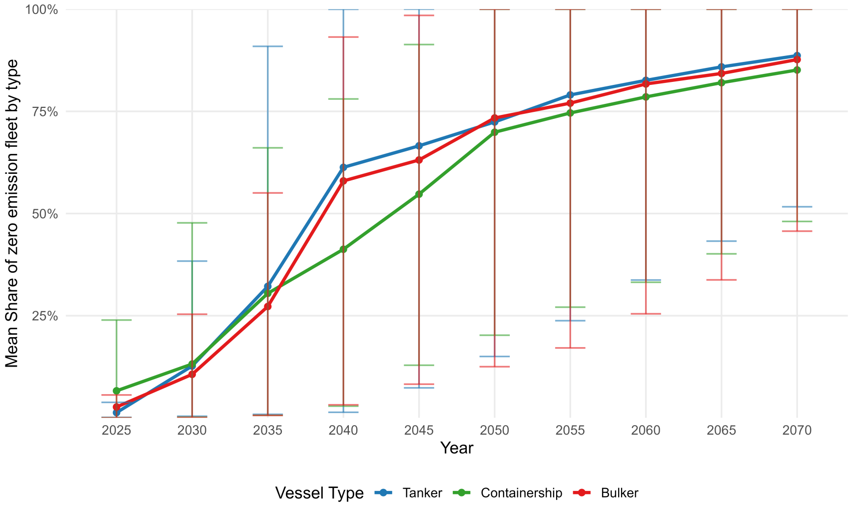


Figure D.15.: Mean share of zero-emission fleet by type. Averaged over scenarios; Early lead for containerships, but they stall relatively due to complex routing and supply chains. However, Tankerships see the fastest average transition, followed by bulkers.

E

SUPPLEMENTARY MODEL OUTPUTS

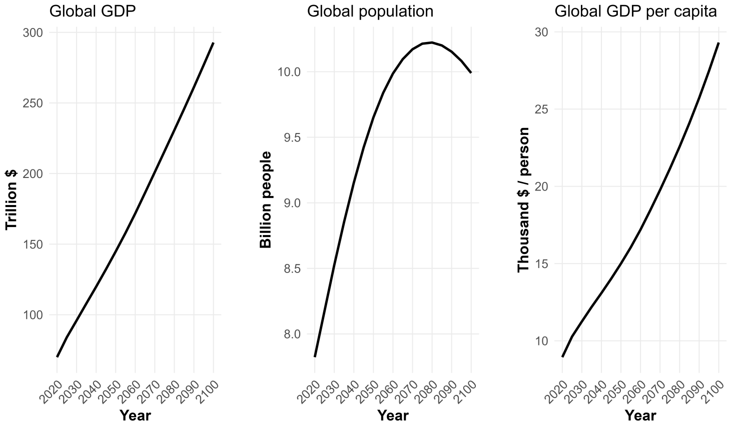


Figure E.1.: Population and gross domestic product (GDP) assumptions used in primary scenarios, aligned with Shared Socioeconomic Pathway 2.

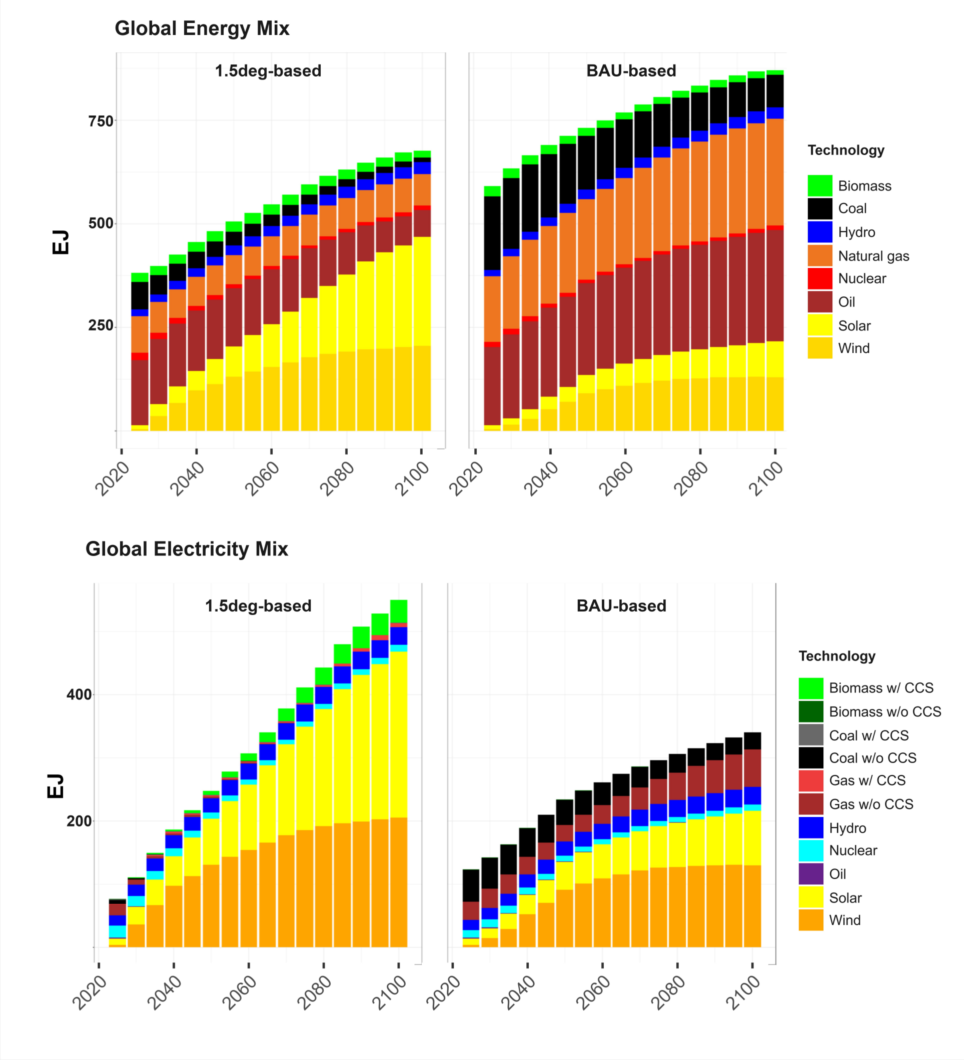


Figure E.2.: Global energy and electricity mix. Global energy mix (top), and global electricity mix (bottom) of baseline-based and 1.5°C-based scenarios in the model.

F

GLOSSARY

The following abbreviations are used in the thesis:

Abbreviation	**Definition**
AFOLU	Agriculture, Forestry and Other Land Use
AR6	IPCC Sixth Assessment Report
AIS	Automatic Identification System
BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture and Storage
BPstats	BP Statistical Review of World Energy
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CEPII	Centre d’Études Prospectives et d’Informations Internationales
CII	Carbon Intensity Indicator
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DNV	Det Norske Veritas (classification society)
DWT	Deadweight Tonnage
EE	Energy Efficiency
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EIA	U.S. Energy Information Administration
EJ	Exajoule
ETS	Emissions Trading System
FT	Fischer–Tropsch synthesis
FTA	Free Trade Agreement
GCAM	Global Change Analysis Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLOTRAM	Global Trade Analysis Model
HFO	Heavy Fuel Oil

HS	Harmonized System (commodity classification)
HVO	Hydrogenated Vegetable Oil
IAM	Integrated Assessment Model
IAMC	Integrated Assessment Modeling Consortium
IEA	International Energy Agency
IFM	International Freight Model
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LFO	Light Fuel Oil
LNG	Liquefied Natural Gas
LR	Learning Rate (electrolyser)
MAE	Mean Absolute Error
MCDA	Multi-Criteria Decision Analysis
MEPC	Marine Environment Protection Committee
MFO	Marine Fuel Oil
ML	Machine Learning
MRV	Monitoring, Reporting and Verification
MSE	Mean Squared Error
NZF	Net-Zero Framework (as proposed at MEPC 83)
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
OPEX	Operating Expenditure
PBL	Netherlands Environmental Assessment Agency
RMSE	Root Mean Squared Error
SEEMP	Ship Energy Efficiency Management Plan
SIN	Shipping Intelligence Network (Clarksons)
SMR	Steam Methane Reforming
SMR+CCS	Steam Methane Reforming with Carbon Capture and Storage
SSP	Shared Socioeconomic Pathway
TEU	Twenty-foot Equivalent Unit
TIAM	TIMES Integrated Assessment Model
ULCV	Ultra Large Container Vessel
UNCTAD	United Nations Conference on Trade and Development
VECM	Vector Error Correction Model
VIF	Variance Inflation Factor
WITCH	World Induced Technical Change Hybrid model

ACKNOWLEDGEMENTS

Looking back, this PhD has been much more than an academic journey. It has been a period of growth, challenge, and transformation, both professionally and personally. Moving far from home, dealing with uncertainty, and building a life in a new place reshaped my perspective in many ways. Along this path, I was fortunate to be surrounded by people whose support, guidance, and presence made all the difference.

First and foremost, I would like to express my sincere gratitude to my supervisors. **Jeroen**, thank you for your constant guidance, support, and the many fruitful discussions we had during our bi-weekly meetings. I learned a great deal from you, not only scientifically, but also in the way you approach problems with clarity and structure. Your support and availability were essential throughout this path. **Dingena**, although our fields were not always perfectly aligned, your support and perspective on the bigger picture of the PhD work were invaluable. Thank you for your trust, your encouragement, and for always being there when it mattered.

I would also like to thank **Massimo**, **Laurent**, **Soheil**, **Johannes**, and **Eduardo**. Beyond being experts in the field, you have been generous with your time and knowledge. Your insights, ideas, and willingness to help shaped many parts of this work, and I have truly benefited from your expertise. I am also grateful to my collaborators in the Magpie project, especially **Juan** and **Andre**, and others involved along the way. Your collaboration and exchange of ideas contributed meaningfully to this project.

To my colleagues and friends at the university, thank you for making the daily PhD life far more enjoyable. I am grateful to all the friends and colleagues who made the work environment warm and human, including **Sara**, **Charlotte**, **Ege**, **Jesper**, **Apostolos**, **Konstantinos**, **Wenhua**, **Nikos**, **Jayvee**, **Miguel**, and many others. The coffees, conversations, and small breaks during long days made a real difference. A special mention to **Skirmantas** and **Kris**; Although you chose different paths, I truly value the friendship we built in our office.

Beyond the university, I was lucky to find a community that felt like family here in the Netherlands. **Pooria**, **Amirhossein**, **Reihaneh**, **Arash**, **Parvin**, **Ahmad**, **Soroush**, **Eszter**, **Mana**, and **Fatemeh**, thank you for your warmth, kindness, and for making even the difficult days feel lighter. Knowing you has been a blessing, and I am deeply grateful for the sense of belonging you brought into my life. I will not forget how you were there for me when it mattered.

To my old friends from my hometown, **Kooshan**, **Reza**, **Hossein**, **Sepehr**, **Ali**, **Mehran**, and **Mohsen**, these friendships have stood the test of time. No matter the distance, they remain strong, real, and irreplaceable. Growing up alongside my closest cousin and oldest friend, **Reza**, is something I will always value deeply in my heart.

From my bachelor years in Tehran, **Vahid**, **Arash**, **Arash**, **Reza**, **Ahoora**,

Nima, and **Sina**, you showed me something valuable about friendship. No matter how much time passes, or how far life takes us from each other, the connection remains intact. And when we meet again, it feels not only the same, but somehow deeper and more meaningful than before.

And then there is Milan, and the people who made that time what it was, **Raman**, **Pooneh**, **Amin**, **Negar**, **Nima**, **Soheil**, **Sareh**, **Navid**, **Sina**, and **Siavash**. Thank you for the memories, the shared experiences, and for continuing to be part of my life. What we experienced together there was rare in its own way, and those moments have stayed with me over time.

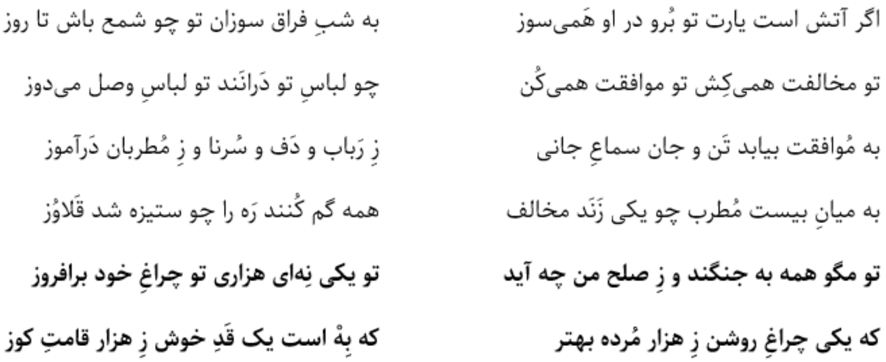
Ahmad and **Soroush**, you deserve a special place here. Our lunches, deep conversations, laughter, and the many moments we shared brought balance, energy, and clarity into this phase of life. And this is only a small part of a story that will continue. Many of these moments were also shared with **Saman**, and they would not have been the same without you. These were not just breaks from work, but part of what made this experience meaningful.

در پایان، دلم می‌خواد از خانواده‌ام بگم؛ از جایی که همه‌چیز برای من از اونجا شروع میشه. **پدر و مادر** عزیزتر از جانم، هر چی دارم از شماست. از مهر بی‌دریغتون، از حمایتی که هیچ‌وقت ازم دریغ نکردین، و از فداکاری‌هایی که شاید هیچ‌وقت کامل درکشون نکنم. همیشه پشت و پناهم بودین، حتی وقتی خودم نمی‌دونستم دارم چی کار می‌کنم. می‌دونم هیچ‌وقت نمی‌تونم اون‌طور که باید جبران کنم، ولی تا آخر عمرم قدردان همه‌چیزتون هستم. سارای عزیزم و حامد عزیزم، و **علی** و **پریای** مهربون، شما برای من فقط خانواده نیستین، یه تکیه‌گاه واقعی هستین. **سارا**، تو خودِ مهر و محبتی برام، و **حامد**، همیشه برام هم الگو بودی، هم مایه افتخار، هم یه رفیق واقعی. و شما دوست‌داشتنی های زندگی من، **امیرعلی**، **پانیسا**، **امیررضا و دلسا**، شما نور چشمای منین. آینده رو میشه تو چشم‌های پاک و روشن شما دید، و آرزوی من فقط اینه که همیشه خوشحال باشین، موفق باشین و زندگی براتون بهترین هارو بخواد. **خانواده عزیز همسرم**، از شما هم صمیمانه سپاسگزارم برای محبت، حمایت و پذیرشی که از من داشتید. خیلی خوشحالم که امروز می‌تونم بگم شما را مثل خانواده خودم دوست دارم و در کنار هم، به یک خانواده تبدیل شدیم. خاله‌های مهربونم، حضورتون همیشه برام پر از آرامش و خاطره‌های خوب بوده. خیلی از قشنگ‌ترین لحظه‌های کودکی‌م با شما گذشته و اینا چیزاییه که همیشه باهام می‌مونه. و البته بقیه اعضای عزیز خانواده‌ام که اسم تک‌تک‌تون اینجا نیومده، اما همیشه در دل من جای دارین و سهمی از این مسیر با من داشتین. از ته دل ممنونم از همه‌تون، برای عشقی که بی‌هیچ چشم‌داشتی بهم دادین.

و در آخر، **ایران**؛ که برای من فقط یک سرزمین نیست، بلکه بخشی از هویت و ریشه‌ای‌ست که در عمق وجودم جاریست. هر جا که باشم، تکه‌ای از من در تو مانده، و آنچه از من می‌روید، ناگزیر، رنگ و بوی تو را با خود دارد. آبادانی دوباره ات آرزویم است.

Finally, **Sana**. It is difficult to put into words what you have been to me during these years. You have been my light, my calm, and my strength. Together, we built a home far from home, and in that space, we built something even more valuable, a shared life shaped by love, understanding, and growth. Your presence gave meaning to this experience beyond anything academic. I am deeply grateful for you, for us, and for everything we are building together.

I would like to conclude this acknowledgement with a poem by **Jalāl al-Dīn Muḥammad Rūmī**, which has been a quiet light along this path.



اگر آتش است یارت تو بُرو در او هَمی‌سوز   به شبِ فراق سوزان تو چو شمع باش تا روز

تو مخالفت همی‌کِش تو موافقت همی‌کُن   چو لباسِ تو دَرانَند تو لباسِ وصل می‌دوز

به مُوافقت بیابد تَن و جان سماعِ جانی   زِ رَباب و دَف و سُرنا و زِ مُطربان دَرآموز

به میانِ بیست مُطرب چو یکی زَنَد مخالف   همه گم کُنند رَه را چو ستیزه شد قَلاوُز

تو مگو همه به جنگند و زِ صلح من چه آید   تو یکی نِه‌ای هزاری تو چراغِ خود برافروز

که یکی چراغِ روشن زِ هزار مُرده بهتر   که بِهْ است یک قَدِ خوش زِ هزار قامتِ کوز

Delft, Spring 2026,
Hesam Naghash

CURRICULUM VITæ

Hesam Naghash

Hesam Naghash was born in Iran in 1994. He pursued his doctoral studies at Delft University of Technology (TU Delft), the Netherlands, between 2022 and 2026, focusing on the decarbonization of international maritime shipping using integrated energy–economy modeling frameworks. His research examined the interaction between global climate policy, trade dynamics, fleet transitions, and the deployment of alternative marine fuels. He holds a Master of Science degree in Energy Engineering from Politecnico di Milano, Italy (2017–2020), where his work centered on energy systems analysis and climate mitigation pathways, and a Bachelor of Science degree in Mechanical Engineering from the University of Tehran, Iran (2012–2017). Before his PhD, he worked as a researcher at the Euro-Mediterranean Center on Climate Change (CMCC) in Italy from 2020 to 2022, contributing to integrated assessment modeling and policy-oriented analysis of climate mitigation, energy transitions, and alternative fuels.

LIST OF PUBLICATIONS

JOURNAL ARTICLES

1. E. Müller-Casseres, F. Leblanc, M. van den Berg, P. Fragkos, O. Dessens, **Naghash, Hesam**, R. Draeger, T. Le Gallic, I. S. Tagomori, I. Tsiropoulos, *et al.* “**International shipping in a world below 2° C**”. in: *Nature Climate Change* 14.6 (2024), pp. 600–607
2. **Naghash, Hesam**, D. Schott, and J. Pruyn. “**Shifting waves of shipping: a review on global shipping projections and methodologies**”. In: *Journal of Shipping and Trade* 9.1 (2024), pp. 1–43
3. **Naghash, Hesam**, D. Schott, and J. Pruyn. “**Evolving shipping activity in climate scenarios: Coupling econometrics with Integrated Assessment Model**”. In: *Ocean Engineering* 322 (2025), p. 120516
4. **Naghash, H.**, Schott, D., Pruijn, J. **“Global maritime decarbonization scenarios: system-wide energy and climate interactions.”** Submitted to *Nature Communications* (Under revision).

CONFERENCE PAPERS

1. **Naghash, H.**, Schott, D., Pruijn, J. **“Evolving Bilateral Shipping in Climate Scenarios: Coupling Econometrics with Integrated Assessment Model.”** IEW 2025.
2. **Naghash, H. “Bilateral Energy Trade Evolution Under Different Climate Scenarios.”** IAME 2024, Valencia, June 2024.
3. **Naghash, H.**, Pruijn, J., Schott, D. **“Future of International Shipping: A Review of Projections and Methodologies of Supply, Demand, and Emissions in the Shipping Sector.”** World Conference on Transport Research (WCTR), Montreal, 17–21 July 2023.