INTERNATIONAL MARITIME ORGANIZATION

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MARINE ENVIRONMENT PROTECTION COMMITTEE
82nd session
Agenda item 7

MEPC 82/INF.8
26 July 2024
Original: ENGLISH
Pre-session public release: ☒

REDUCTION OF GHG EMISSIONS FROM SHIPS

Report of the Comprehensive impact assessment of the basket of candidate GHG reduction mid-term measures – full report on Task 1 (Literature review)

Note by the Secretariat

SUMMARY

Executive summary:	This document provides the full report on Task 1, Literature review, of the comprehensive impact assessment of the basket of candidate GHG reduction mid-term measures as conducted by WMU.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 2
Related documents:	MEPC 80/17, MEPC 80/17/Add.1; MEPC 81/7, MEPC 81/7/Add.1; MEPC 82/7, MEPC 82/7/1, MEPC 82/7/2, MEPC 82/7/4; MEPC 82/7/4/Add.1, MEPC 82/7/4/Add.2, MEPC 82/7/4/Add.3, MEPC 82/7/4/Add.4, MEPC 82/INF.8/Add.1, MEPC 82/INF.8/Add.2, MEPC 82/INF.8/Add.3 and MEPC.1/Circ.885/Rev.1

Introduction

1 The Comprehensive impact assessment of the basket of candidate mid-term GHG reduction measures consists of five distinct and interrelated tasks (MEPC 82/7/4, paragraph 5). This document provides the full report on the literature review conducted by the World Maritime University (WMU), as set out in the annex.

Action requested of the Committee

2 The Committee is invited to take in account the information provided in this document, when considering documents MEPC 82/7/4 and MEPC 82/7/4/Add.1.

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Established under the auspices of the International Maritime Organization
a specialized agency of the United Nations

Task1: Literature Review - Final Report

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Document Title:			
Systematic Review of relevant literature related to the IMO comprehensive impact assessment of the basket of mid-term measures – Task 1			
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Version	Comments	Date	Authorized by
01	Draft	24 November 2023	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
02	Draft	22 December 2023	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
03	Draft	23 January 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
04	Draft	26 February 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
05	Draft	25 March 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
06	Draft	22 April 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
07	Final Document	21 May 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
08	Final Document	7 June 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn

09	Final Document	18 June 2024	Professor Dr. Aykut I. Ölçer; Dr Fabio Ballini, Dr Alessandro Schönborn
External QA/QC reviewers		Yujiro Wada (Japan), Ioannis Moutzouris (United Kingdom), Om Prakash Sha (India), Li Lu (China)	
Sensitivity		CONFIDENTIAL	
Number of pages:		288 (including cover page and one Appendix)	

Acronyms

ABS	American Bureau of Shipping
ASEAN	Association of Southeast Asian Nations
BAU	Business-As-Usual
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CBDR	Common but Differentiated Responsibilities
CBDR&RC	Common But Differentiated Responsibilities and Respective Capabilities
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CDM	Clean Development Mechanism
CH_3OH	Methanol
CH_4	Methane

CII	Carbon Intensity Indicator
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
DCS	Data Collection System
DME	Dimethyl Ether
DNI	Disproportionately Negative Impacts
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
ECSA	Emission Compliance Service Agreement
ECTS	Emission Cap-and-Trade System
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
EJ	Exajoule
EMSA	European Maritime Safety Agency
ESC	Energy Supply Contracting
ESS	Energy Storage System
ETS	Emissions Trading System

EU	European Union
FCM	Flexibility Compliance Mechanism
GCF	Green Climate Fund
GDP	Gross Domestic Product
GEF	Global Environment Facility
GFS	Greenhouse Gas Fuel Standard
GHG	Greenhouse Gas
GHGL	Greenhouse Gas Levy
GMN	Global Maritime Technology Cooperation Centres Network
GT	Gross Tonnage
GWh	Gigawatt hours
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
ICS	International Chamber of Shipping
IEA	International Energy Agency
IEA APS	International Energy Agency Announced Pledges Scenario
IEA NZE	International Energy Agency Net Zero Emissions by 2050 Scenarios
IEA STEPS	International Energy Agency Stated Policies Scenarios

ILO	International Labour Organization
IMF	International Monetary Fund
IMO	International Maritime Organization
IMRB	International Maritime Research Board
IMSF&F	International Maritime Sustainability Funding and Fuel
IMSF&R	International Maritime Sustainability Funding and Reward
Intercargo	International Association of Dry Cargo Shipowners
IRENA	International Renewable Energy Agency
ISWG-GHG	Intersessional Working Group on Reduction of Greenhouse Gases Emissions from Ships
ITF	International Transport Workers' Federation
IUCN	International Union for Conservation of Nature
LBG	Liquid Biogas
LCA	Life Cycle Assessment
LDC	Least Developed Country
LLDC	Landlocked Developing Country
LNG	Liquefied Natural Gas
LR	Lloyd's Register

LSBCI	Liner Shipping Bilateral Connectivity Index
LSCI	Liner Shipping Connectivity Index
MDO	Marine Diesel Oil
MEC	Maritime Energy Contracting
MEPC	Marine Environment Protection Committee
MET	Maritime Education and Training
METI	Maritime Education and Training Institution
MGO	Marine Gas Oil
MJ	Megajoules
MMM Center	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MRV	Monitoring, Reporting and Verification
MTCC	Maritime Technology Cooperation Centre
N_2O	Nitrous Oxygen
NDC	Nationally Determined Contribution
NH_3	Ammonia
NMFT	No More Favourable Treatment
NO_x	Nitrogen Oxides

NZE	Net Zero Emission
OECD	Organization for Economic Co-Operation and Development
OPEX	Operating Expenditure
OSV	Offshore Supply Vessels
PIC	Pacific Island Countries
PIP	Port Incentive Program
PPP	Purchasing Power Parity
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRIF	Pacific Region Infrastructure Facility
PSC	Port State Control
PV	Photovoltaics
RD&D	Research, Development, and Deployment
RGGI	Regional Greenhouse Gas Initiative
ROPAX	Roll-On/Roll-Off Passenger
SCFI	Shanghai Containerized Freight Index
SFFSM	Self-Financing Fuel-Saving Mechanism
SIDS	Small Island Developing States
SMR	Small Modular Reactor

SO_x	Sulphur Oxides
TCO	Total Cost of Ownership
TEU	Twenty-foot Equivalent Unit
TtW	Tank-to-Wake
UMAS	University Maritime Advisory Services
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNFCCC	United Nations Framework Convention on Climate Change
UN SDG	United Nations Sustainable Development Goal
US	United States
VLSFO	Very Low Sulphur Fuel Oil
WHR	Waste Heat Recovery
WMU	World Maritime University
WtW	Well-to-Wake
ZESIS	Zero-Emission Shipping Incentive Scheme
ZEV	Zero-Emission Vehicles

Disclaimer

This report has been completed by the World Maritime University. It contains the report on Task 1 on the literature review of the Comprehensive impact assessment of the basket of mid-term GHG reduction measures.

Whilst this report has been commissioned by the International Maritime Organization (IMO), the information contained within this report represents the views of its authors. It should not be interpreted as representing the views of the IMO, or the Steering Committee on the comprehensive impact assessment of the basket of candidate mid-term measures, or the States that are represented on the Steering Committee.

This comprehensive impact assessment of the basket of mid-term GHG reduction measures consists of five distinct but interrelated tasks for which different reports have been prepared. Task 1 of the comprehensive impact assessment of the basket of mid-term GHG reduction measures is being undertaken solely to assist IMO's Marine Environment Protection Committee (MEPC) in making evidence-based decisions. Any information included in this report is provided solely for analytical purposes and should not be interpreted as suggestions or recommendations for how the basket of mid-term GHG reduction measures should be designed. The policy combination scenarios and any other information included in this report are provided solely for analytical purposes and should not be interpreted as suggestions or recommendations for how the basket of mid-term GHG reduction measures should be designed.

The designations employed and the presentation of material on any map in this report do not imply the expression of any opinion whatsoever on the part of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

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EXECUTIVE SUMMARY AND KEY FINDINGS

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Context and methodology

MEPC at its eightieth session approved the terms of reference for the conduct of a comprehensive impact assessment of the basket of candidate mid-term measures delivering on the reduction targets of the *2023 IMO Strategy on Reduction of GHG Emissions from Ships* and invited the Secretary-General to establish the Steering Committee to act as a focal point for the Committee during the conduct of the comprehensive impact assessment. Following consideration, the Steering Committee agreed to recommend that WMU carry out the literature review as Task 1 of the comprehensive impact assessment.

The aim of this literature review is to identify relevant literature findings on the potential impacts of a basket of candidate mid-term GHG reduction measures comprised of a technical element, namely a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity, and an economic element, on the basis of a maritime GHG emissions pricing mechanism. This literature review has focussed in particular on the following issues: a review of the most recent published fuel/technology transition pathways for shipping, including reviews of the final energy demand and supply, and the forecast fuel and technology mixes; an analysis of the determinants of the maritime transport costs, and the pass-through of compliance costs; the findings from existing assessments of potential impact of GHG mitigation measures on the eight impact criteria in the 2023 IMO Strategy; existing literature on potential approaches to address (e.g. avoid, remedy, mitigate) impacts on States; and existing literature on the use of revenues of GHG pricing mechanisms.

The methodology applied in this literature review comprised a systematic literature review. The systematic literature review was undertaken by specifying relevant search terms in an abstracts and citation database of peer-reviewed literature, followed by a review of the literature found in this database, a review of the literature found using an internet search engine, as well as a review of literature references specified in this literature. In addition to the systematic literature review, an internet search engine was used to access relevant grey literature (non-peer reviewed documents).

Relevant literature for assessment in this review was selected by the WMU research team as well as submitted by members of the Steering Committee of the comprehensive impact assessment of the mid-term measures and the IMO Secretariat by 5 January 2024 at the latest. The literature review does not therefore take into account any new literature after 5 January 2024.

Main findings of subtask 1: A review of most recent fuel/technology transition pathways for shipping

A comprehensive systematic literature review of the most recent fuel technologies and transition pathways, highlighting advantages and disadvantages of various fuels and technologies, including safety concerns and life-cycle impacts, was carried out. The analysis showed that a wide range of technologies could help reducing the GHG emissions from shipping. Wind and solar energy capture could reduce the fuel energy needs and various fuels, such as biofuels, hydrogen, methanol and ammonia, synthetic fuel oils, as well as battery electric energy storage and nuclear power, could cover the remaining energy needs.

Main findings of subtask 2: On the energy demand side, a review of the final energy demand (EJ and GWh equivalence) and energy intensity (MJ/ tonne miles) considered for the shipping sector, both current and projections to 2030, 2040 and 2050

The literature review found that the projections for future seaborne trade vary widely in the literature, depending on the scenarios developed in the studies. There appeared to be consensus in the literature that transport work, i.e. the amount of cargo transported over a certain distance (measured in tonne miles) would increase significantly during the decades between 2022 and 2050, with estimates of this increase varying between around 66-125%.

The literature predictions for the final energy demand in shipping during the decades between 2020 and 2050 varied widely. Studies assuming net-zero emissions by around 2050 expect a final energy demand for shipping ranging between 3.42 EJ and 11.9 EJ for 2050.

The shipping energy intensity projected by the IEA and IRENA net-zero by 2050 scenarios predict continuously decreasing shipping energy intensities from around 0.16 MJ/tonne · mile in 2022 to around 0.064 - 0.080 MJ/tonne · mile by the year 2050.

Main findings of subtask 3: On the energy supply side, a review of the fuel and technology mixes (in EJ, GWh and percentage share) linked to each demand scenario, both current and projections to 2030, 2040 and 2050

Predictions for the future energy supply of individual fuels vary, but several studies in the literature report that ammonia is expected to reach the highest fraction in shipping energy supply amongst the fuels, with absolute energy levels between 3.41 and 5.02 EJ or 180 to 270 M tonnes (i.e. million tonnes) of ammonia per annum in 2050. Another important share in the fuel energy supply was generally ascribed to biofuels and methanol, with energy estimates for those predicting any biofuels at all being 0.69 to 3.47 EJ in 2050, and energy estimates for methanol around 0.31 and 2.6 EJ in 2050. Estimates for hydrogen energy supply to shipping range between 0.56 to 2 EJ in 2050 (note – this refers to the direct use of a hydrogen as a fuel, rather than the use of hydrogen as a feedstock to produce other fuels).

The shipping energy share in 2050 was reported to be forecast as 35-100% for ammonia, 7-25% biofuel, 3-19% methanol, and 7-19% hydrogen based on the literature reviewed. Assumptions in the various literature scenarios vary widely.

A clear gap in the literature is the lack of explicit description of shipboard renewable energy sources, such as wind and solar energy, that will contribute to the energy supply to shipping. None of the studies examining the overall energy need or supply to shipping assessed in this literature review explicitly stated how much energy is expected to come from wind or solar sources. Wind and solar energy are energy sources, and should not be reported as energy efficiency measures, which is physically incorrect.

Main findings of subtask 4: An analysis of the determinants of maritime transport costs and of pass-through of compliance costs within the maritime supply chain

The assessed literature suggests that the factors influencing the costs associated with maritime transport are diverse and encompass geographical, operational, and market-specific considerations. Challenges arising from these considerations can be addressed by regulatory interventions and investment strategies, among others.

Adopting a basket of mid-term GHG reduction measures would have potential impacts. In the literature reviewed, increases in maritime logistics costs from rising fuels, projected at different levels (10%, 20% and 50%), revealed modest changes in trade flows, with impacts on global GDP being of less than 0.1%. However, it was noted that SIDS and LDCs may be expected to experience more pronounced adverse effects.

The literature review suggests that a maritime GHG emission pricing mechanism would not lead to an equivalent percentage increase in maritime or overall transport costs. This is because transport costs are only one part of the broader trade costs. Therefore, the impact of a maritime GHG pricing mechanism on imported goods' prices would be less significant than the impact on maritime transport costs.

In the literature reviewed, increases in shipping costs are projected to range from 0.4% to 16%, with the effect on import prices predominantly below 1%. While the proposed measures are expected to result in a general uptick in maritime logistics costs, encompassing shipping and trade costs, the magnitude of this increase remains relatively constrained.

The potential benefits of improving port infrastructure and trade facilitation measures are significant. The literature suggests that better port infrastructure could lead to a 4.1% reduction in average maritime transport costs worldwide, while improved trade facilitation measures could result in a 3.7% decrease in costs. Particularly for LDCs, the greatest benefits could be derived from enhanced trade facilitation, which could lead to an 8.6% decrease in costs, compared to a 0.7% decrease achieved by improving port infrastructure.

In recognizing the potential disproportionate impact on SIDS and LDCs from regulatory interventions, the literature assessed suggested that disbursing a significant proportion of revenues generated through carbon pricing mechanisms to these States could assist in mitigating adverse effects, ensuring a more equitable distribution of costs and benefits, alleviating their burden, and paving the way for a more sustainable and inclusive maritime transport landscape.

Main findings of subtask 5: Findings from existing assessments of the potential impact of introducing GHG mitigation measures on shipping costs and, by extension, on the eight impact criteria identified in the 2023 IMO GHG Strategy

The exploration of GHG mitigation measures in maritime transport within the literature reviewed offered a wide array of insights, revealing a multi-faceted landscape and a need for addressing the complexities of sustainability in this sector. At the heart of this lies the discussion about carbon pricing mechanisms, recognized in the reviewed literature as one of the key tools for guiding the industry towards net-zero GHG emissions. Through emissions taxes and trading (carbon pricing) schemes, these tools aim to incentivize the adoption of zero or near-zero GHG alternatives and to correct the competitive disparity between traditional fossil fuels and cleaner options.

However, implementing carbon pricing mechanisms has its complexities. The literature highlights the importance of establishing corresponding support structures to facilitate their effectiveness. Such structures must support decarbonization efforts and consider the economic implications, ensuring a delicate balance between environmental and financial sustainability. Furthermore, the assessed literature advocates a hybrid approach, echoing the 2023 IMO GHG Strategy, which emphasizes the symbiotic relationship between technical interventions and economic instruments. This holistic approach is essential to overcome the various market barriers hindering sustainability progress.

In parallel, the literature review shed light on the effectiveness of direct regulatory approaches. Although more straightforward in their implementation, these measures offer potential cost-effective solutions to reduce the competitiveness gap and advance decarbonization efforts. Furthermore, regional initiatives can be crucial in guiding decarbonization efforts, with some countries poised to lead the transition through abundant resources and expertise. The potential for knowledge sharing between regions, particularly between developed and developing countries, holds promise in promoting a more equitable global transition towards sustainability.

Implementing carbon pricing mechanisms requires overcoming challenges such as emissions allocation, stakeholder engagement, technical expertise and a strong foundation of reliable data to inform decision-making processes effectively. Therefore, the literature review highlights the urgent need for empirical evidence and rigorous research to guide future policy formulations and industrial practices.

As the literature review highlights, price elasticities across products and industries are indicative of different carbon pricing sensitivities. That suggests that the efficacy of mitigation measures is dependent on the traded goods. Among others, products having low value/weight ratios like fossil fuels and ores show large carbon emission reductions under moderate carbon pricing in contrast to high-value goods such as furniture and motor vehicles which show smaller reductions. It demonstrates that the intrinsic character of goods should be taken into account in assessing the impact of carbon pricing.

Moreover, the reviewed literature highlighted that a phased increase in carbon pricing rates, e.g. from $75 per tonne CO_2 in 2030 and $150 per tonne in 2040, could drive substantial CO_2 reductions but slightly raise shipping costs. Still, revenues generated from such policy measures in the reviewed literature, which are estimated to be around $75 billion in 2030 and $150 billion by 2040, could partially offset the economic impacts.

But the reviewed literature also highlighted that implementation of carbon pricing mechanisms raises several challenges and considerations including emission allocation, revenue management and stakeholder engagement. Those challenges require competence development and a solid data infrastructure.

This literature review concludes that there is an absence of exemplar schemes for shipping.

In summary, the review highlights the need of holistic, data-driven approaches to drive the sector towards a sustainable future, ensuring that economic prosperity aligns harmoniously with environmental stewardship.

Main findings of subtask 6: Existing literature on potential approaches to address (e.g. avoid, remedy, mitigate) impacts on States

The literature review on potential strategies for mitigating the potential impacts of mid-term measures on States is divided into two sections: section one addresses pathways describing how to mitigate, remedy and avoid the impact of the technical measures on States, and section two describes pathways of how to mitigate, remedy and avoid the impact of the economic measures on States.

Mitigating pathways in relation to technologies

The literature review identified 15 possible approaches of mitigating the potential impacts arising from ships adopting decarbonization technologies and fuels. The pathways may be listed as follows: (Inter) national policies and regulatory frameworks, international collaboration and diplomacy, international capacity building and technology transfer (including skilling), investments and financing mechanisms, social, economic and environmental impact assessments, research and development support, adaptive governance and new business models, monitoring and management, public and stakeholder engagement, awareness and public acceptance improvement, infrastructure improvement, labour skilling and safety measures, economic diversification strategies, phased-in implementation, and exemptions. These pathways were considered in light of the eight impact criteria in IMO's GHG strategy.

Mitigating approaches in response to economic impacts

The literature review identified also the following list of possible approaches to mitigating the potential impacts arising from economic measures: a step-based increase of the carbon price (in case of a levy) to avoid extreme development and trade cap, with a view to facilitating the political implementation of a carbon pricing mechanism; boosting motivational effects of the carbon pricing mechanism in lower tax rates which could be achieved by a higher transparency in ships' emission reporting and energy efficiency rating, the introduction of a rebate mechanism and a differentiated carbon levy; assessing sustainable business models by facilitating the energy transition through a proper definition of stakeholders' interaction; considering the effect of free riders; conducting stakeholder analysis to prepare the scene for proper designing of communication channels, business models and standard connections between them; building a national dataset as lack of information is one of the major barriers to equitable energy transition in particular in the case of SIDS and LDCs; supporting slim organizations; and a well-designed carbon revenue distribution network by establishing appropriate legal and administrative frameworks, procedure for managing revenue flows, effective stakeholder engagement and accountability procedures.

Main findings of subtask 7: Existing literature on the use of revenues of GHG pricing mechanisms

Based on the results of the literature review, an overview of lessons learned on carbon revenue collection and distribution in the other industries were identified. The literature reported various ways of distributing carbon revenue in the other industrial sectors: Containing the burden on target groups (e.g. exemptions, preferential tax rates, rebates, gifting, and feebate systems), using revenue to lower other taxes, promoting renewable energy and energy efficiency, using emission offsets, financing climate and environmental projects, constructing new infrastructure and retrofitting existing infrastructure, earmarking revenues for administrative costs, funding of research and development (R&D), adapting to the impacts of climate change, allocating revenue into general national budgets, and funding of cross-cutting measures.

Focused on the maritime industry, there is a wide range of projected carbon revenue in different studies and proposals, which is primarily due to the wide range of recommended carbon prices and assumptions. According to the literature reviewed, carbon pricing (in the case of a levy) could be collected by flag administrations, port State administrations, an international institution, a network of bunker suppliers, or directly from each individual ship to its electronic account.

In the study over carbon pricing mechanisms in international shipping, revenue generation and distribution were identified as key issues. In addition to achieving shipping decarbonization goals, the reviewed literature suggested recycling of carbon revenues from the shipping industry could pave the way for achieving broader climate aims and promoting greater equity, and that these revenues could be used for activities both in-sector and out-of-sector. The literature review identified the following ways carbon revenue could be distributed in-sector and out-of-sector.

In-sector distribution: financial support for RD&D activities; financial support for the process of policy making, administrative and enforcement costs of the carbon pricing mechanism, development of a rebate mechanism at ports, financial support for vessels' retrofit and fleet renewal, support for alternative fuel production, enhancement of maritime transport energy infrastructure and services, and capacity building, education and training.

Out-of-sector distribution: development of an instrument in response to the CBDR&RC principle, and capacity building and technology transfer to SIDS and LDCs.

1. INTRODUCTION

The vision of the *2023 IMO Strategy on Reduction of GHG Emissions from Ships* states that IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible, while promoting, in the context of this Strategy, just and equitable transition. The 2023 IMO GHG Strategy outlines a timeline for GHG reduction measures: short-term measures to be finalized and agreed by 2023, mid-term measures to be agreed and finalized by 2025 (with additional ones between 2023 and 2030), and long-term measures to be agreed and finalized beyond 2030. This Strategy has as a guiding principle the need to consider the impact on States before the adoption of GHG reduction measures, where particular attention should be paid to the need of developing countries, in particular LDCs and SIDS.

'MEPC 80 also invited the Secretary-General to establish the Steering Committee to act as a focal point for the Committee during the conduct of the comprehensive impact assessment in accordance with the *Revised procedure on assessing impacts on States of candidate measures* (MEPC.1/Circ.885/Rev.1) and the terms of reference for the comprehensive impact assessment.'. Following consideration, the Steering Committee agreed to recommend that WMU carry out the literature review in line with the agreed work.

This qualitative systematic literature review was carried out as part of the IMO comprehensive impact assessment of the basket of mid-term measures. The literature review provides a comprehensive analysis of contemporary fuel and technology transition pathways in the shipping industry. The investigation unfolds in two key dimensions—energy demand and supply. On the demand side, the inquiry scrutinizes final energy demand and energy intensity for shipping, encompassing current metrics and projections up to 2050. In addition, the energy supply side involves evaluating fuel and technology mixes associated with various demand scenarios, considering both the present state and future projections for 2030, 2040 and 2050.

The review extends to an in-depth analysis of the determinants of maritime transport costs and the pass-through of compliance costs within the maritime supply chain. It also seeks to extract insights from existing assessments on the potential impacts of GHG mitigation measures on shipping costs and, by extension, their alignment with the eight criteria identified in the 2023 IMO GHG Strategy. Furthermore, it explores the existing literature on approaches to address the impacts on States, including strategies like avoidance, remedy and mitigation, and delves into the utilization of revenues generated from GHG pricing mechanisms.

The impacts on States of a measure/combination of measures should be assessed and taken into account as appropriate before adoption of the measure, as described by IMO's *Revised Procedure for Assessing Impacts on States of candidate measures*. There are up to four steps in the procedure where Step 4 is for conducting a comprehensive impact assessment commencing with a Literature review (Task 1). Subsequent tasks are distinct but interrelated: Assessment of impacts of the measure on the fleet (Task 2), Assessment of impacts of the measure on States (Task 3), Complementary qualitative/quantitative stakeholders' analysis, including relevant illustrative case studies (Task 4), and Identification of areas of missing data, quality assurance and quality control (QA/QC), uncertainty and sensitivity analyses and integration between various tasks (Task 5).

WMU assessed relevant technical and scientific papers as well as IMO documents and grey literature and reports to provide a literature review focused on a basket of candidate mid-term GHG reduction measures comprised of both a technical element, namely a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity, and an economic element, on the basis of a maritime GHG emissions pricing mechanism.

How will the basket of candidate mid-term measures change international shipping?

1.1. Review questions

No.	***Main question***	***Sub-questions***
1	***A review of most recent fuel/technology transition pathways for shipping***	1. *What are the future fuels and technologies including their advantages and disadvantages?* 2. *What are the transition pathways?*
2	***On the energy demand side, a review of the final energy demand (EJ and GWh equivalence) and energy intensity (MJ/miles-tonne) considered for the shipping sector,***	1. *What are the different scenarios that affect energy demand in shipping?* 2. *What global factors affect shipping demand (e.g. GDP, population, energy*

	both current and projections to 2030, 2040 and 2050	*intensity, seaborne trade, and carbon intensity of electricity production).*
3	***On the energy supply side, a review of the fuel and technology mixes (in EJ, GWh and percentage share) linked to each demand scenario, both current and projections to 2030, 2040 and 2050***	*1. How much fuel energy is projected to be available?* *2. What are fuel costs expected to be?*
4	***An analysis of the determinants of maritime transport costs and of pass-through of compliance costs within the maritime supply chain***	*1. What are the factors of maritime transport that influence the costs associated?* *2. How do various factors within maritime transport impact associated costs?* *3. What elements contribute to the cost pass-through analysis within the maritime supply chain?* *4. How does the pass-through of costs occur within the maritime supply chain?*
5	***Findings from existing assessments of the potential impact of introducing GHG mitigation measures on shipping costs and, by extension, on the eight impact criteria identified in the 2023 IMO GHG Strategy***	*1. What are the impacts of candidate mid-term measures various determinants of maritime transport costs, and for their part, on the costs of imported products?* *1.1. How do these measures impact the volume of exports/imports and associated costs within Small Island Developing States (SIDS)?* *1.2. How much this is expected to cost to actors in the maritime supply chain?* *2. Are there substantial gaps in the existing body of literature concerning this subject matter?*

6	***Existing literature on potential approaches to address (e.g. avoid, remedy, mitigate) impacts on States***	*3. What are the approaches to mitigate, remedy and avoid the impact of adoption of future fuels and technologies on States?* 4. *What are the mitigating approaches in response to economic impacts?*
7	***Existing literature on the use of revenues from GHG pricing mechanisms***	*1. What is the projected climate revenue from the proposed maritime GHG emissions pricing mechanisms?* *2. How can carbon revenues be collected?* *3. How can carbon revenues be distributed?* *4. What distribution framework can be used?* *5. Which actors can access carbon revenues (recipients)?*

1.2. Methodology outline

The methodology adopted in this report is a systematic literature review. Systematic reviews tend to be less biased and maintain relevancy as they are designed to be comprehensive and grasp large amount of literature, that cannot be handled in a random search. This means that for each task (1-6), search terms were prepared, and search was executed in one of the largest databases "Scopus" and "Google Scholar".

Scopus is a comprehensive database that covers multiple academic disciplines, providing users access to a wide range of scholarly articles, conference proceedings, and patents. It ensures extensive coverage of scientific literature and supports research by enabling users to track citations, analyse research trends, and evaluate the impact of academic publications.

Google Scholar is a freely available search engine for scholarly literature. It catalogues scholarly articles, theses, books, conference papers, and patents, offering a convenient platform for researchers to explore academic content.

Scopus includes grey and white literature, but some industrial and technical reports are hard to get in this database, so we conducted some manual searches using the Google database. It is worth noting that this report presents the results appearing in the literature without personal opinion.

Relevant literature for assessment in this review was selected by the WMU research team as well as submitted by members of the Steering Committee of the comprehensive impact assessment of the mid-term measures by January 2024 at the latest.

2. METHODOLOGY

2.1. Methodology for subtasks 1 to 3

The methodology applied in this literature review was a combination of systematic literature review, specifying relevant search terms in an abstracts and citation database of peer-reviewed literature, followed by a review of the most relevant texts.

2.1.1. Systematic Search

A systematic literature review was conducted to investigate the most recent fuel/technology transition pathways for shipping decarbonization including energy supply and demand. The search terms were composed to yield maximum number of relevant studies for each of the required subtasks (1-3) (see figure 1 that shows all the systematic literature review processes including search and filtering).

The following search terms were composed to collect the maximum number of relevant studies for each of the required subtasks (1-3). See the full view of search and restrictions in figure 1.

Subtask 1. A review of most recent fuel/technology transition pathways for shipping.

- **Search terms** including restrictions ((ship* OR maritime) AND (alternative fuel OR hydrogen OR H2 OR ammonia OR NH3 OR methanol OR CH3OH OR E-methanol OR biofuel OR biogas OR electrification OR battery OR mid-term GHG reduction measures OR renewable energy OR wind OR solar)).

Subtask 2. On the energy demand side, a review of the final energy demand (EJ and GWh equivalence) and energy intensity (MJ/miles-tonne) considered for the shipping sector, both current and projections to 2030, 2040 and 2050;

- **Search terms** (TITLE ("Global" OR "World" AND "Energy" AND "Demand"))

Subtask 3. On the energy supply side, a review of the fuel and technology mixes (in EJ, GWh and percentage share) linked to each demand scenario, both current and projections to 2030, 2040 and 2050;

- **Search terms** (TITLE ("Global" OR "World" AND "Energy" AND "Supply"))

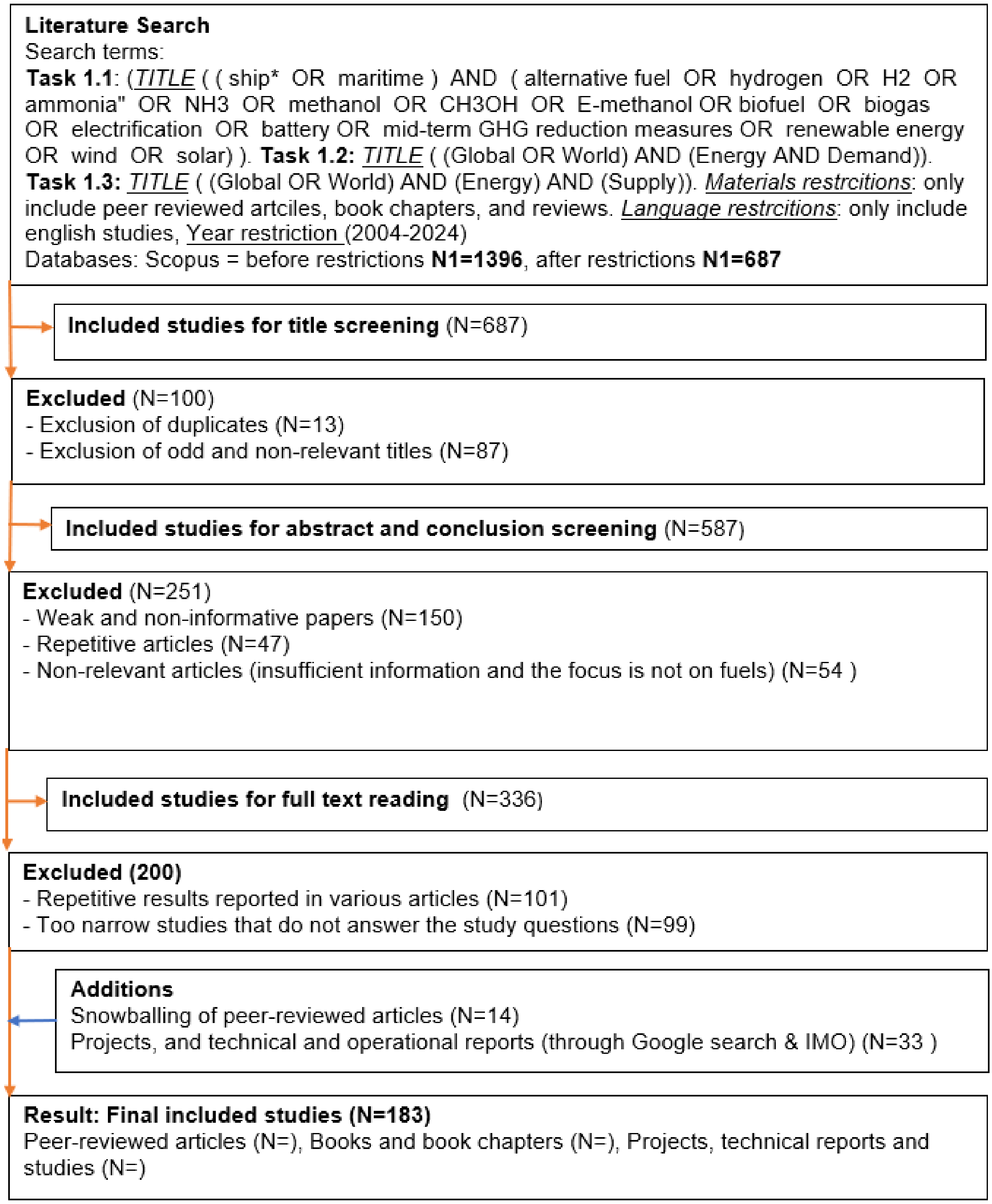

Figure 1. Search and filtering results for subtask 1.1-3

Note: Final studies included will be updated later on, i.e. after we account for all the studies.

2.1.2. Filtering stages

After the first collection of studies, filtering stages were conducted. First stage is the title screening, second stage is the abstract and conclusion screening, third stage is full text reading, last stage is additions through snowballing and the documents that IMO shared with

WMU (which were shared by the Members of the Steering Committee on the comprehensive impact assessment of the basket of candidate mid-term measures to include in the analysis). **Figure 1** above shows all of these stages for the three subtasks and the final studies included in the analysis.

2.1.3. Synthesis

Subtask 1.1. technology pathways

After having collected the literature, a framework was built to guide the analysis. First, taxonomies of technologies were built (11 taxonomies: ammonia, hydrogen, fuel cells, biofuel (including DME and biodiesel), methanol and ethanol, fully electric batteries, renewable energy capture (solar), renewable energy capture (wind energy), carbon capture and storage, nuclear energy, and hybrid power systems). Second, introduction of each technology including its advantages and disadvantages were collected from various studies and technical and industrial reports. Third, a comprehensive reference table was built to include data retrieved from various studies (articles and reports) based on eight criteria (i.e. study focus, technology type, technology potential, GHG abated, cost of technology, what is the case study or project the study addressed, the result of the study, and the reference of the study). See table A in the Appendix (Technology pathways). The table has key results, and is always referred to, so readers can use the table and pursue particular studies if they need. Fourth, studies that addressed the environmental life cycle analysis (LCA) were assembled together and a separate table (using criteria similar to the previous table A) summarised the result of the literature, see table B in the Appendix.

Subtask 2 and 3. Energy supply and demand

With respect to energy supply and demand, the systematic literature review did not yield many studies to utilise. Thus, the data was extracted mainly from key industry or grey literature reports because few peer-reviewed articles discussed such topics.

2.2. Methodology for subtasks 4 to 5

This systematic review has been performed in accordance with the Systematic Reviews and Meta-Analysis (PRISMA) methodology (Page et al., 2021).

The search process was implemented through electronic databases and journals like Scopus and Google Scholar, scanning published articles, peer-reviewed studies, and eligible systematic reviews to uncover pertinent materials linked to the research query.

The studies included in our analysis have met the criteria outlined in the following table, which delineates both inclusion and exclusion parameters.

Table 1. Inclusion and exclusion criteria

INCLUSION CRITERIA	**EXCLUSION CRITERIA**
Year since 1996	Year till 1995
Main focus of the papers	Ancillary topics
Peer-reviewed journals	Conference proceedings
Grey literature	Repeated articles published on different journals with the same authorship (the earliest considered)
Access to full text	Lack of access to full text
English language	Language other than English
Analysis of the determinants of maritime transport costs and of costs pass-through within the maritime supply chain	
Key words: "maritime transport* costs", "transport* costs", "cost of transport*", "trade costs", "cost of trad*" "affect*", "govern*", "determin*", "cause*" "influenc*" impact* ("carbon pric*", "MBM", "market based",ects), ("maritime",ship*)	*Key words:* SUBJAREA, "bioc", "medi", "math", "eart", "arts", "phys", "mate", "ceng", "immu", "engi", "agri", "comp"

TITLE-ABS-KEY(("market based measures", MBM), ("ship*","maritime", "transport", "air*"))	
"Levy", "DCS", "levy-based", "MBM", "IMSF", "IMSB", "IMSF&R", "GSF"	
"ZESIS", "ZEV", "ZEF", "levy", "feebate", "FLL", "WtW"	
"ECTS", "SEU"	
"IMSF&R", "CII"	
"IMSF&F", "GFI", "SRU", "DU", "RU"	
"ISWG-GHG 12/3/5", "GFS", "LCA", "SRS", "SRU", "GFI", "GRU", "ISWG-GHG 13/4/8", "FCM", "FCU"	
"SIDS", "IDC*", "small island developing states", "least developed countries", "maritime transport* costs", "transpt* costs", "cost of transpt*", "trade costs", "cost of trad*"	

The initial findings were exported to a spreadsheet after each search across the specified databases. Upon removing duplicates, scrutiny of titles and abstracts ensued to pinpoint pertinent studies aligning with the inclusion and exclusion criteria. This evaluation was independently undertaken by the authors who assessed the suitability of criteria by reviewing a random subset of included and excluded studies after the preliminary screening stage. During this phase, all the studies that did not satisfy the predetermined exclusion criteria were carefully and thoroughly eliminated from further consideration, ensuring that only the most relevant and suitable studies were retained for further analysis and evaluation. Any discrepancies were deliberated upon and resolved to achieve consensus.

A representation of the study selection procedure can be found in figure 2.

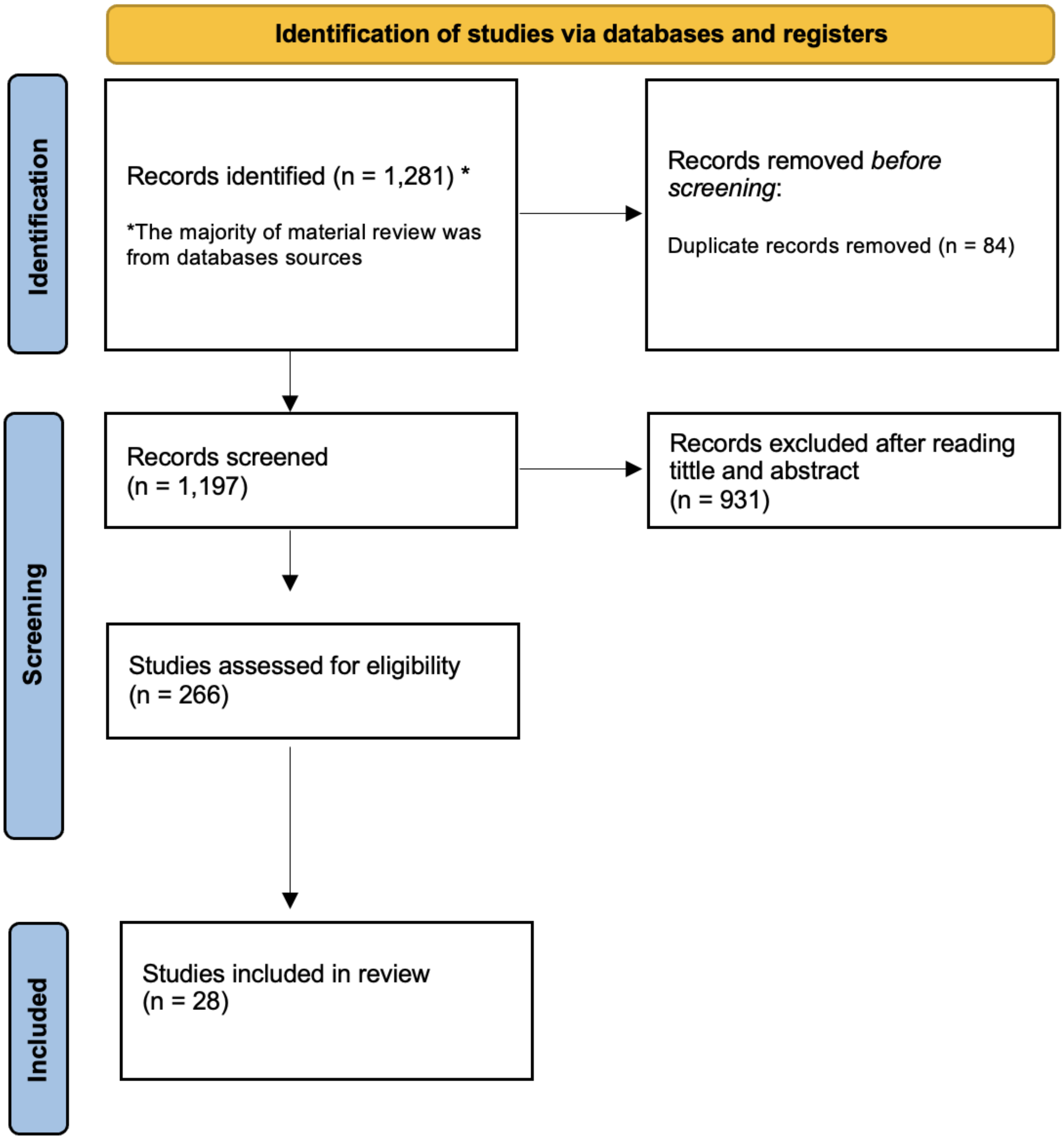

Figure 2. Diagram describing the study selection process for systematic review

2.3. Methodology for subtask 6

Following the methodology in each subtask, we have conducted a systematic search using the Scopus database. The search terms are as follows: for the *technologies and fuels* we used "TITLE ((shipping OR maritime transport) AND (fuels OR technologies OR "IMO GHG Strategy")

AND (mitigation OR remedy OR just transition))." Results yielded two studies that are not relevant. That means that there are no dedicated studies toward this topic and most of the work is scattered in many articles. We have conducted a similar Google search to obtain reports that addressed this topic from a wider perspective, such as just transition etc. We have gathered around 15 studies and reports.

Throughout the search, it was noted that most of the studies addressed shipping decarbonization measures and discussed the use of the revenues from GHG emissions pricing mechanisms (or Market-Based-Measures) as a key approach to mitigate the impact of the measures (fuels and technologies or pricing mechanisms) on States and this is discussed in subtask 7 (use of revenues and pricing mechanisms). No specific study showed how States themselves can avoid, remedy, and/or mitigate the impact of the use of technologies and fuels by ships. Therefore, this subtask zoomed out and gathered literature from various industrial and technical reports, and other relevant studies that addressed mitigation in decarbonization implementation and the just transition approaches. The results built various taxonomies and thus are divided into: 1) approaches to mitigate, remedy, and/or avoid the impact of the use of technologies and fuels on States, and 2) approaches to mitigate, remedy and/or avoid the impact of the use of GHG emissions pricing mechanisms on States.

2.4. Methodology for subtask 7

As was expected, a systematic literature review for this topic was not appropriate, mainly due to scarcity in peer-reviewed articles relevant to maritime carbon revenue distribution. However, the Scopus database was explored with the following combination of keywords:

TITLE-ABS-KEY ((market-based AND measure) OR (carbon AND pricing) OR (carbon AND tax) OR (bunker AND levy) OR (emissions AND trading AND system))

AND

TITLE-ABS-KEY ((international AND shipping) OR (shipping AND industry) OR (maritime AND transport))

AND

TITLE-ABS-KEY ((revenue) OR (recycling) OR (income) OR (earning) OR (collect) OR (distribution))

In the end, 25 articles were identified, of which 7 were determined to be appropriate for inclusion in the report after screening. As a result of follow-up research, more than 40 other documents, including industry reports and grey literature, have been added.

3. RESULTS FROM THE LITERATURE REVIEW

3.1 Results for subtasks 1 to 3

A comprehensive and systematic literature review of the most recent fuels and technology transition pathways was conducted and is provided in full in the Appendix. It contains the fuel taxonomies and highlights advantages and disadvantages for each fuel and technology, including safety concerns and life cycle approaches. In addition, tables representing the various literature studies for all fuels (table A in the Appendix), and life cycle approaches (table B in the Appendix) are provided highlighting different criteria extracted from the studies, thereby offering details that enable further perusal.

Reaching net-zero GHG emissions from international shipping close to 2050 requires knowledge of the future shipping energy needs by fuel and technology. The literature provides historical data on energy demand, transport work and energy intensity of shipping (IMO, 2020; IMO, 2023; Clarksons, 2023). The historical development of international shipping energy demand has been reported indirectly by the Fourth IMO GHG Study (IMO, 2020), the IMO Data Collection System (DCS) (2023), and by the Clarksons Research online database (Clarksons, 2023), and is shown in figure 3. The data shows that the energy demand of international shipping increased progressively after 2000, and soared in the final years leading up to the global financial crisis of 2008. After 2008, a reduction in final energy demand and a stabilisation at a lower level can be observed. As of today, no clear downward trend in final energy demand is visible, but it can be observed that the world seaborne trade has been steadily increasing as shown in figure 4, despite a small temporary reduction following the global financial crisis of 2008. Figure 5 shows the historical development of energy intensity of international shipping. The data indicates a clear and consistent downward trend in the energy intensity of international shipping which explains why the total final energy demand of international shipping has remained relatively stable (figure 3), despite a continuous increase in seaborne trade (figure 4). This may suggest successful technical and operational implementation of energy efficiency measures in the global fleet.

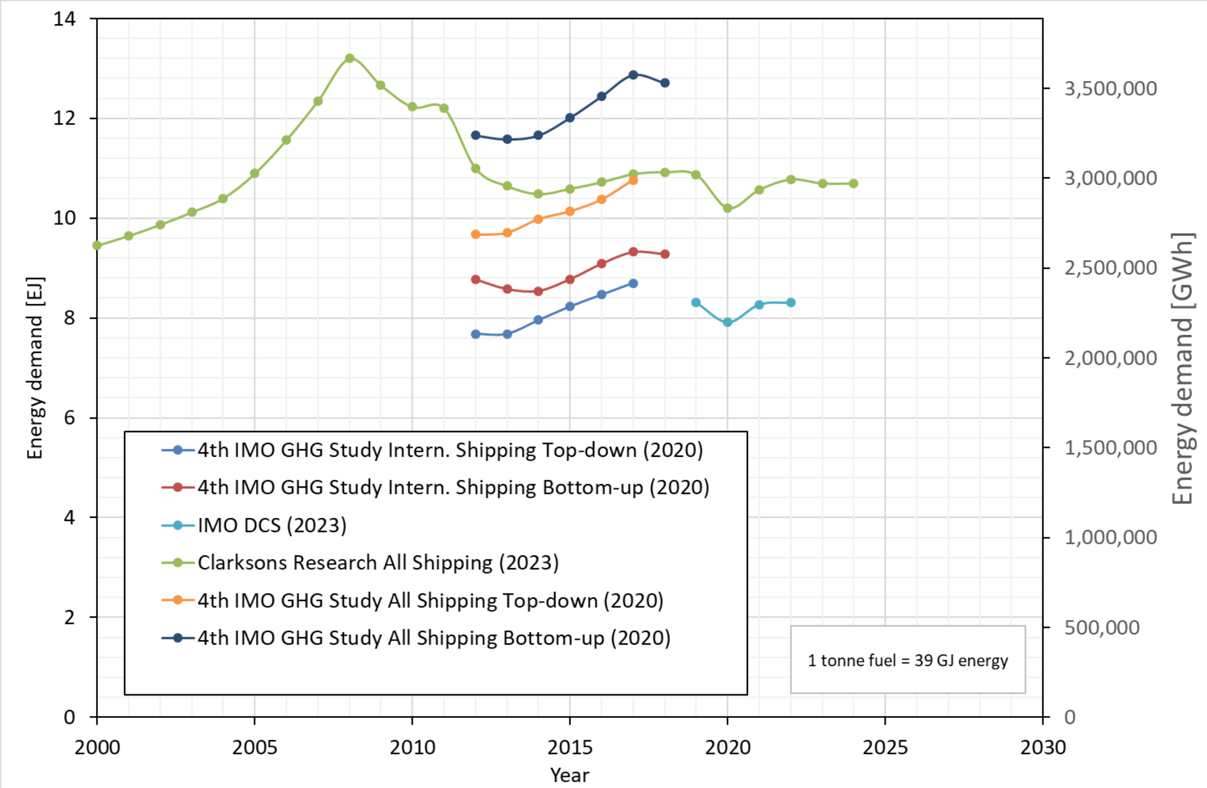

Figure 3. Historical development of final energy demand of international shipping[1]

1 According to the IMO Fourth GHG study, section 1.3. Scope (page 30), the inventory includes global emissions of GHGs and relevant substances emitted from ships of 100 GT and above engaged in both domestic and international voyages. The emissions are presented as totals and disaggregated to ship types and –size categories. All shipping includes both domestic and international versus international shipping (only engaged in international shipping).

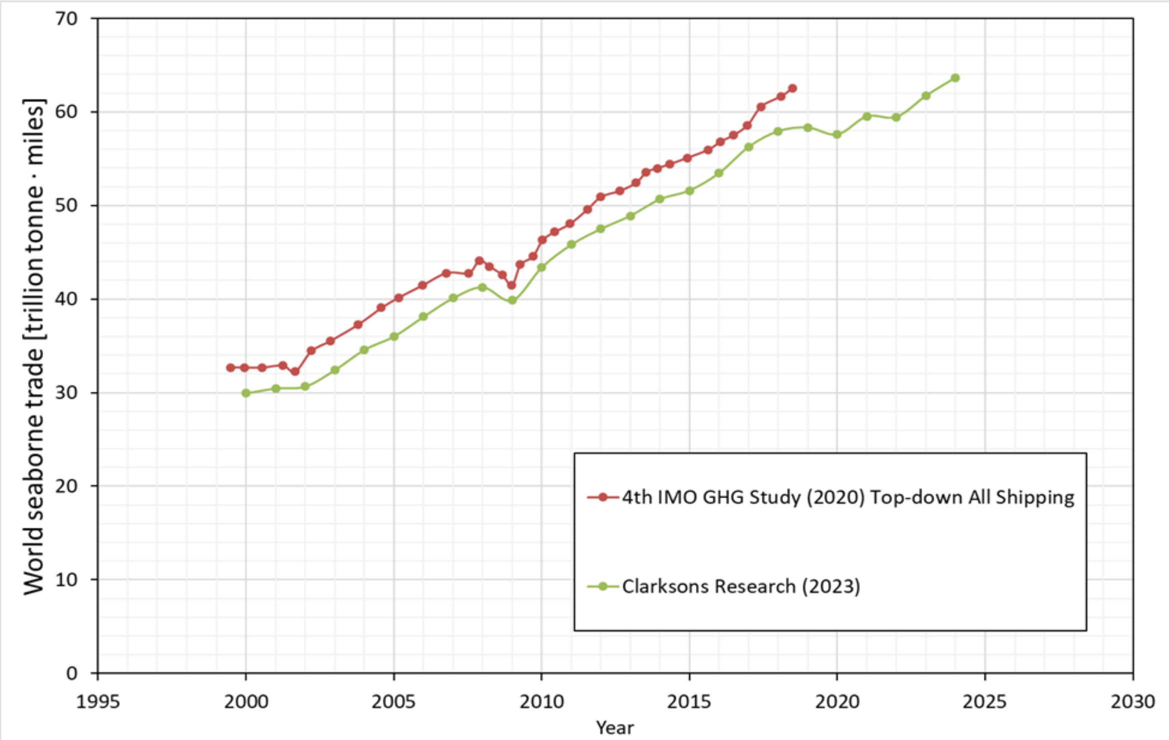

Figure 4. Historical development of world seaborne trade in terms of transport work

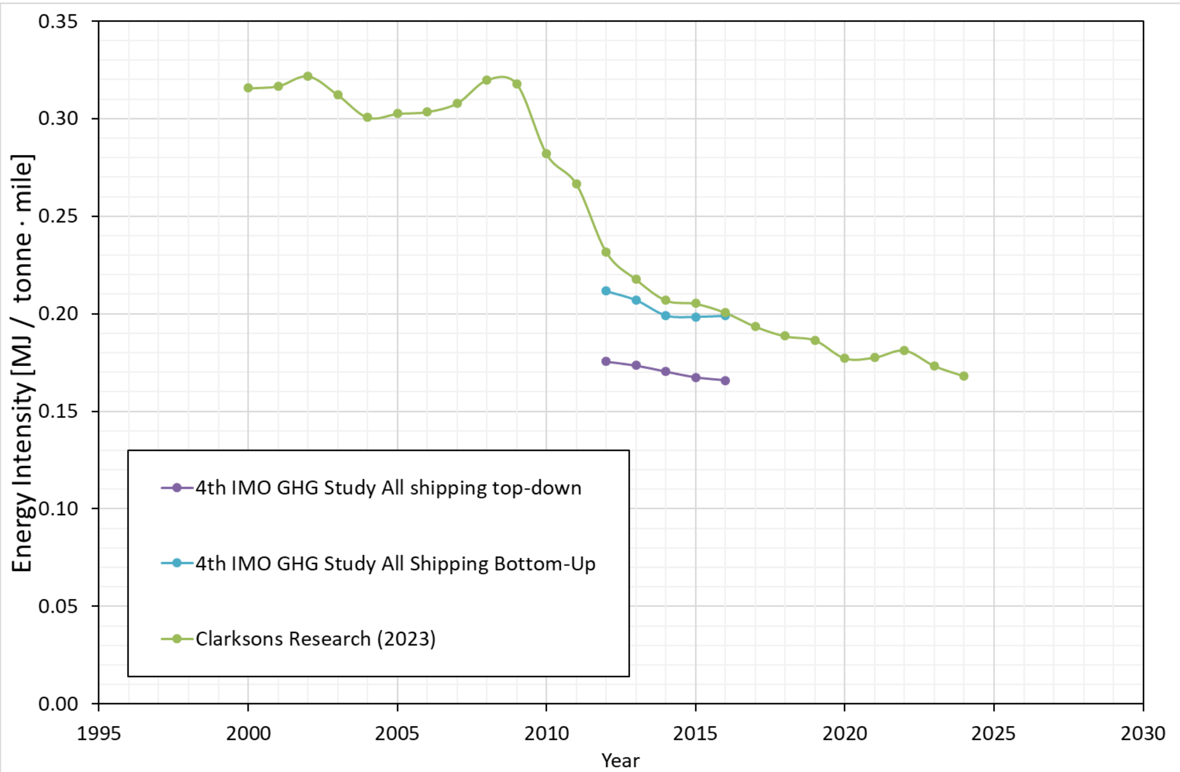

Figure 5. Historical development of shipping energy intensity

The fuels used to make up the historical data up to today almost exclusively use energy from fossil fuel oils, with a limited amount of liquefied natural gas (LNG), liquefied petroleum gas (LPG), and very small quantities of methanol, hydrogen and electricity currently used.

Future projections for the final energy demand of shipping required the development of scenarios that model key factors influencing the energy demand, such as, inter alia, technical energy efficiency, operational energy efficiency, assumptions regarding the development and implementation of policy and regulations, the development of maritime trade and the development of the carbon intensity of electricity production. The projection of final energy needs for international shipping may also depend on the future development of GDP and world population development. Assumptions regarding the prices of fuels and the types of fuels used for shipping may also influence these projections.

The results of the literature review provide projections for the final energy demand for shipping for the years 2020-2050 in a number of studies (IMO 2020; IRENA, 2021; MMM Center, 2021; ABS, 2022; IEA, 2023; Ricardo-DNV, 2023; and DNV 2023). Figure 6 provides an overview of the projections of final energy demand from international shipping for the three decades ranging from 2020 to 2050.

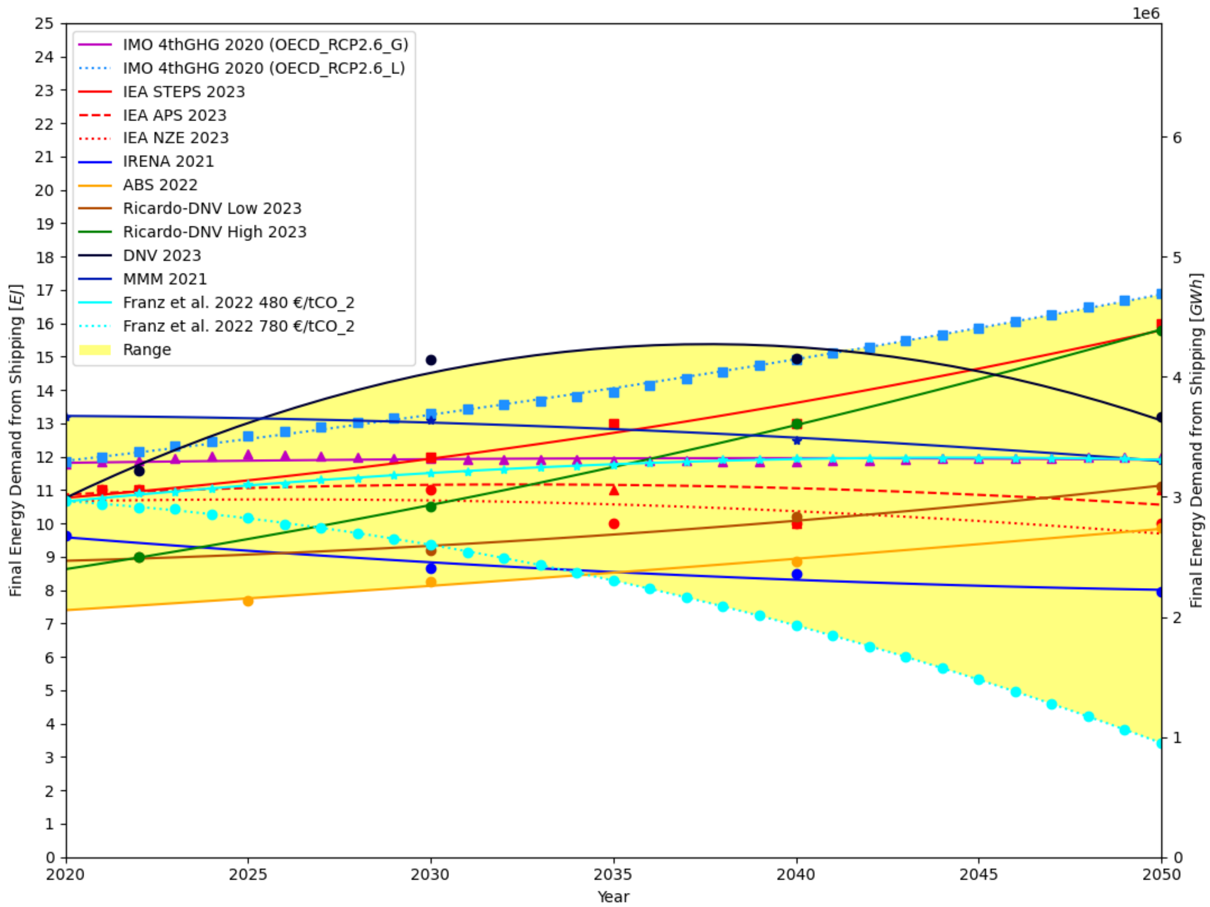

Figure 6. Future projections of final energy demand from international shipping

The results show that the data range varies widely between the different studies and scenarios developed, as indicated by the light-yellow shading. Interestingly, the studies do not show consensus on the absolute level of 2020 energy demand. As expected, future projections deviate, according to the scenarios developed. For example, the IEA stated policies scenario (STEPS) implies that the current 2023 IMO GHG Strategy goals would not be met. It projects an increase in final energy demand from around 11 EJ to about 16 EJ by the year 2050. The IEA announced pledges scenario (APS) assumed an almost stable final energy demand towards 2050, at around 11 EJ. The IEA (2023) APS scenario is expected to meet the requirements of the 2023 IMO GHG Strategy, which has a target of reaching net-zero around 2050.

Other reports, such as DNV (2023), projected a temporary increase in the final energy demand from 11 EJ to around 15 EJ by 2030, before reducing again to around 13 EJ by 2050. IRENA (2021) and ABS (2022) reported some of the lowest projections of final energy demand, with the final energy demand in the IRENA 1.5°C scenario steadily decreasing and the energy demand in the ABS Base scenario steadily increasing.

Unfortunately, not all studies report a comprehensive set of data and assumptions for the reader to understand all projections. The most comprehensive, transparent and complete studies are those reported by the IEA (2023), which provide clear assumptions about the shipping energy intensity projected for the decades between 2020-2050 (figure 7), future projections of the total transport work (figure 8), future projections of global GDP (figure 9), development of world population (figure 10) and projections for the GHG intensity of electricity generation (figure 11).

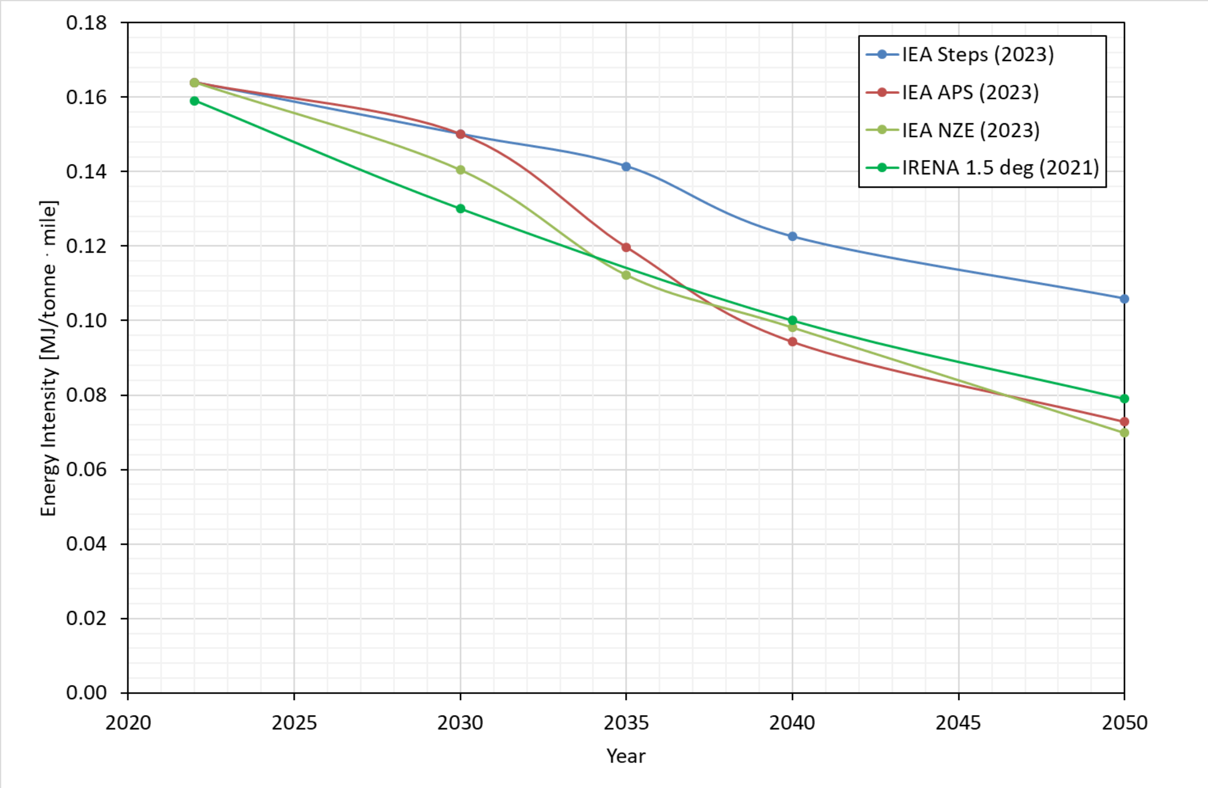

Figure 7. Future projections of shipping energy intensity

The IEA and IRENA studies project continuously decreasing shipping energy intensities from around 0.16 MJ/tonne · mile in 2022 to around 0.064 - 0.080 MJ/tonne · mile by 2050.

Little technical information is provided in these studies as to how this reduction in shipping energy intensity will be achieved. A clear gap that remains in the literature is the quantification of renewable energy generation, such as primary energy captured from wind and solar energy on board ships. Wind propulsion, wind-assisted propulsion or solar energy are often not explicitly mentioned in the literature. They can be represented as an energy source, alongside the fuels, yet their absence in the literature may suggest that they are often assumed to be an energy efficiency measure. It remains unclear from the literature reviewed, how much wind energy is assumed to contribute to the reduction of demand in energy from fuels, and how much other energy efficiency measures, such as drag reduction measures or energy conversion efficiency improvements in ship power-plants are expected to contribute to the reduction in energy demand from fuels.

The assumptions for the transport work of international shipping shown in figure 8 have been reported for the three scenarios developed by the IEA (2023) and for the 1.5°C scenario reported by IRENA (2021). The data shows that the IEA (2023) STEPS scenario, which is not aligned with the 2023 IMO GHG Strategy, and the IEA (2023) APS scenario, which is aligned with the goals of the 2023 IMO GHG Strategy, both use the same high assumption for global transport work. The IEA (2023) NZE scenario and the IRENA (2021) 1.5°C scenario employ the lowest assumptions for transport work in seaborne trade.

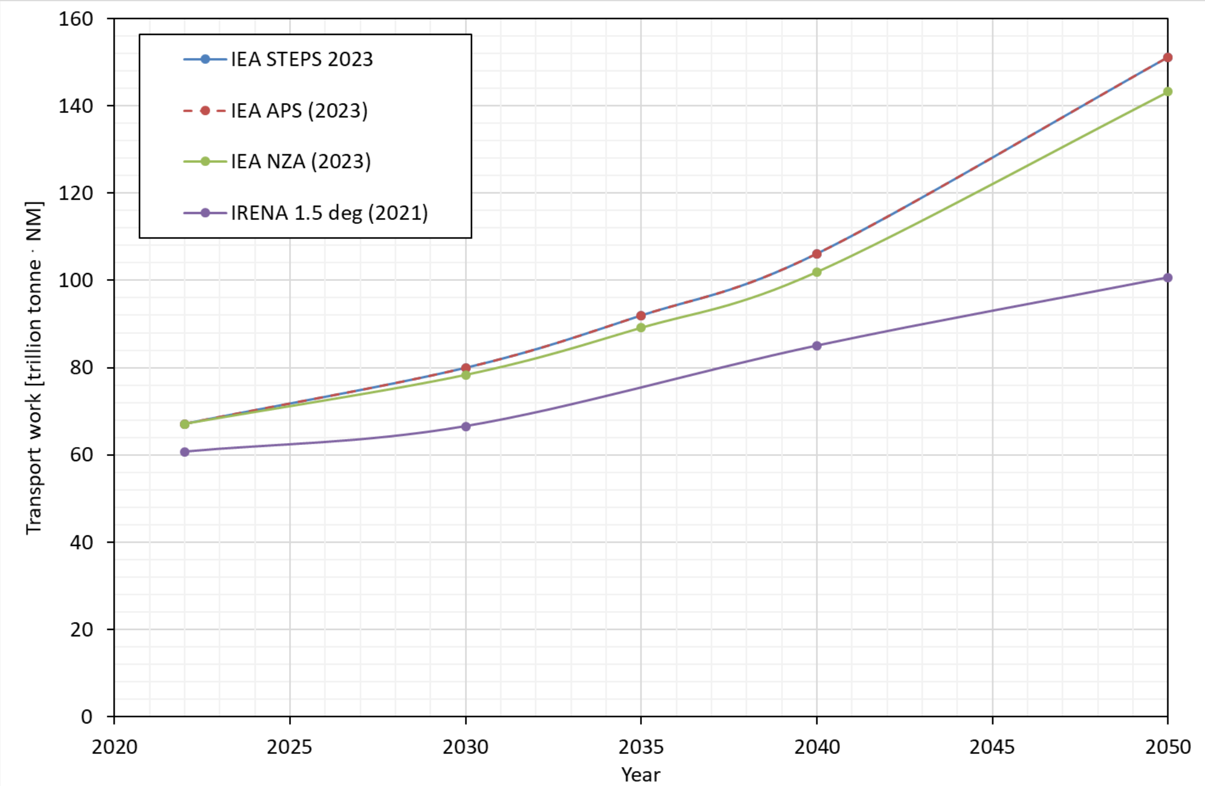

Figure 8. Future projections of total transport work of international shipping

The IEA (2023) was the only one to clearly report assumption on GDP on Purchasing Power Parity (PPP) and world population. These projections were the same (the lines are superimposed on one another) and monotonically increasing for all IEA (2023) scenarios, as can be seen in figure 9 and figure 10. Figure 10 shows that the world population was assumed to increase from around 8,000 million people in 2020, to just below 10,000 million people by 2050 for all three IEA (2030) scenarios.

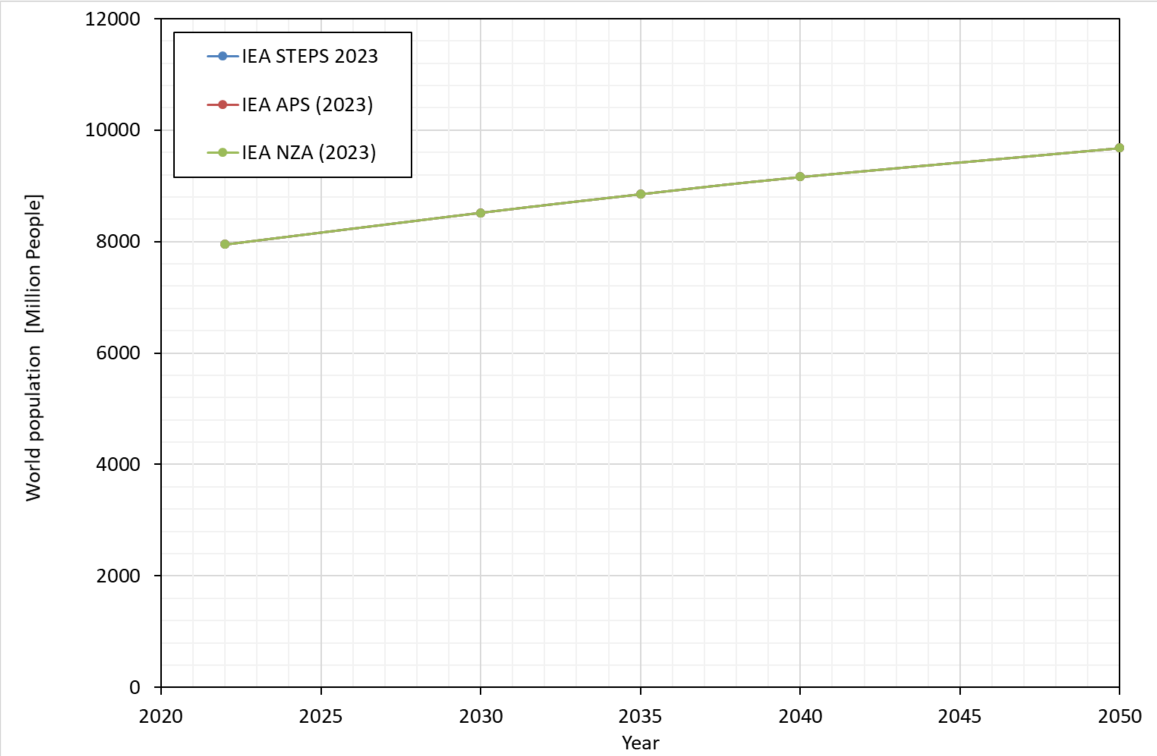

Figure 9. Future projections of GDP (lines are identical and overlayed)

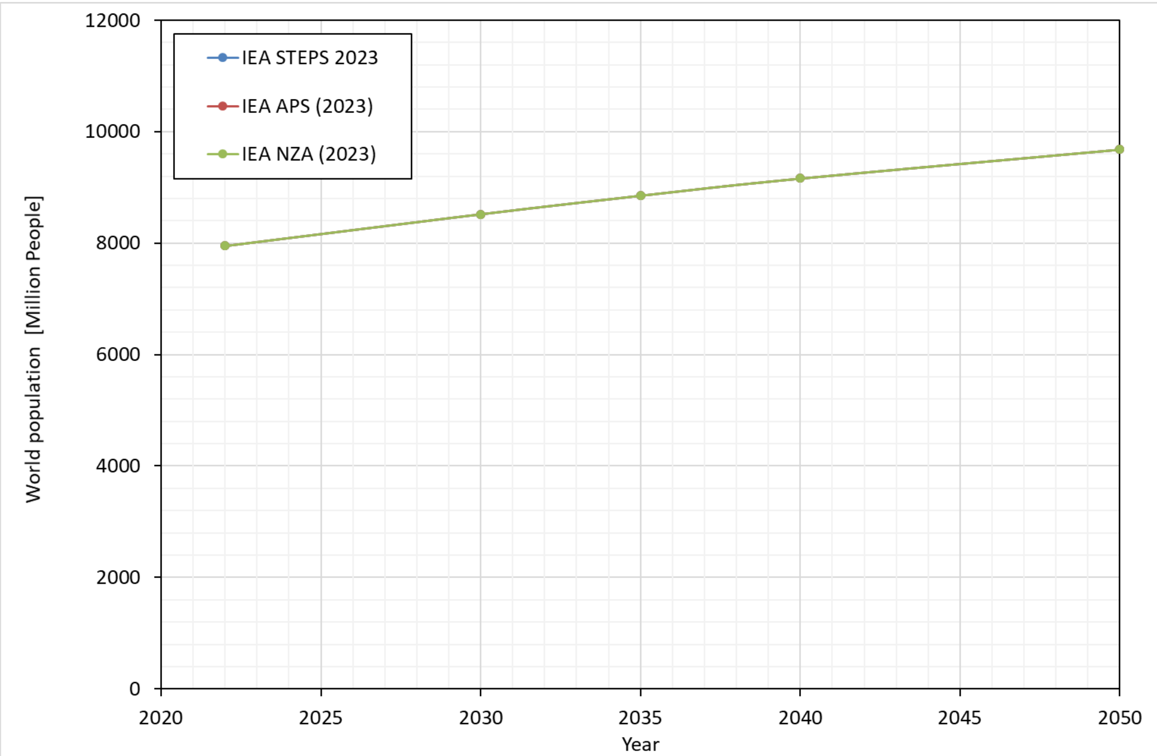

Figure 10. Future projections of world population

An interesting assumption that was included in the reporting of the IEA (2023) scenarios was the GHG intensity of electricity generation from 2020 to 2050 for the three scenarios, shown in figure 11. Large differences are visible in the rate at which the GHG intensity of electricity generation reduced in those three scenarios. The only scenario to reach net-zero emissions and even yield negative GHG emissions was the IEA (2023) NZE scenario. Based on this scenario, negative emissions such as those obtained from the implementation of Bioenergy with Carbon Capture and Storage (BECCS) are likely to prove essential for reaching net-zero emissions. This is because regardless of the alternative fuels or technologies used, the operation of a ship will entail the emission of small amounts of GHG emissions, for example from the production of vessels, or leakage of fuels. These low-level GHG emissions will need to be offset somehow, for example from suitable fuel production methods.

The assumptions made in the various studies are not always reported. The most information about the assumptions was provided in the forecasts made by IEA (2023), as can be seen in table 2.

Table 2. Overview of assumptions reported in studies forecasting fuel mixes

Assumption	Shipping Energy Intensity	Transport Work	GDP	Population	GHG Intensity of Electricity production	CO_2 price
IEA (2023)	Yes	Yes	Yes	Yes	Yes	Yes
IRENA (2021)	Yes	Yes	Yes	Yes	Yes	Yes
ABS (2020)	Yes	Yes	No	No	No	No
DNV (2023)	Yes	Yes	Yes	Yes	Yes	Yes
Franz et al. (2022)	Yes	Yes	No	No	Yes	Yes

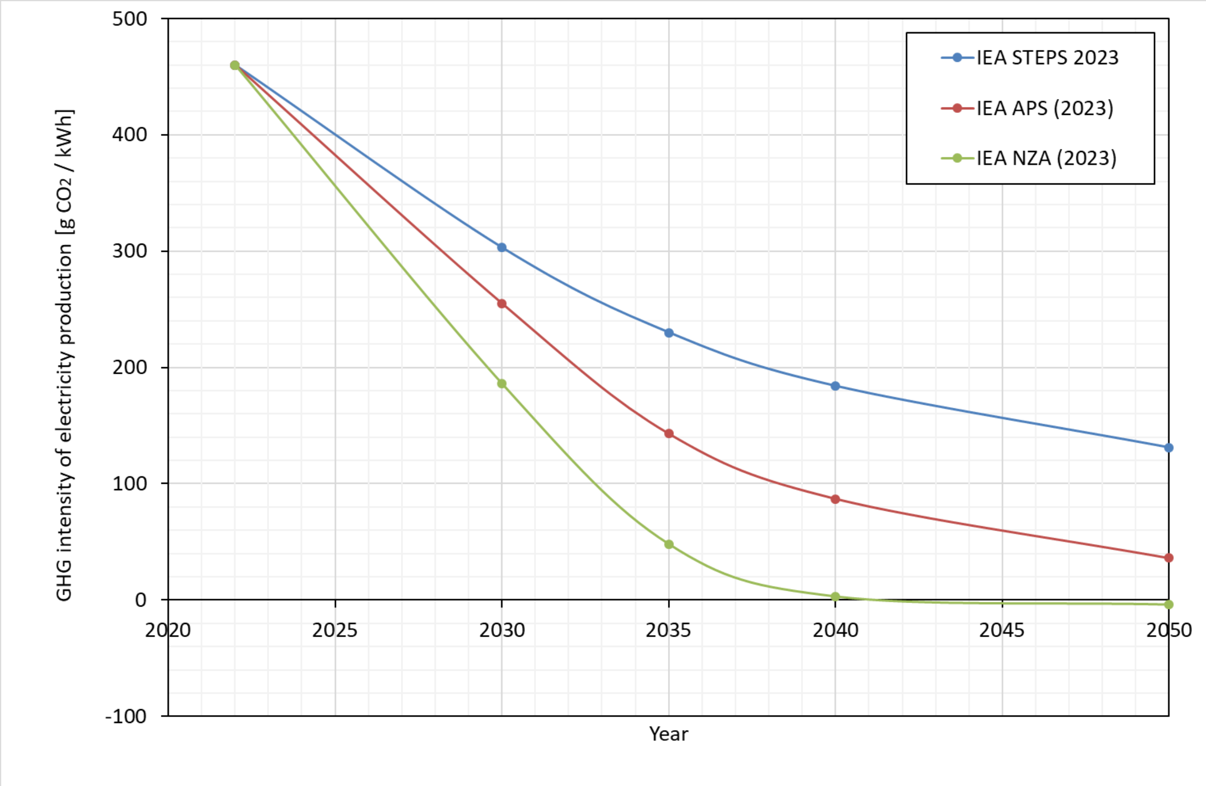

Figure 11. Future projections of GHG intensity of electricity generation

A number of studies (ABS, 2020, IRENA, 2021, Franz et al.;2022; DNV 2023, and IEA, 2023) provide information as to the fractions and absolute amounts of fuels necessary to meet future fuel demand. As mentioned before, a gap is noted in the literature reviewed in that no study explicitly addressed the quantification of wind or solar energy capture on board ships, as an energy input. This is a definite shortcoming of the literature studies reported herein.

The projected fractions of future fuel energy in percentages have been reported by IEA (2023), IRENA (2021), ABS (2020), DNV (2023), and Franz et al. (2022) (scenario C assuming 780 €/tonne CO_2 (Carbon tax)), and have been summarised in figure 12. The data in figure 12 shows that all listed studies predict that the majority of shipping fuel energy in the year 2030 will be derived from fossil sources. The fraction of zero or near-zero GHG emission fuels for the year 2030 was projected to be between 10-20% of the total fuel energy used in shipping. In the year 2030 most scenarios predict that biofuels will have the largest share amongst the zero or near-zero GHG emission fuels, bar the ABS (2020) scenario, predicting methanol to take the highest share among the zero or near-zero GHG emission fuels in that year.

For the year 2040, the predictions regarding alternative fuel use vary more widely, ranging from only 27% for the ABS (2021) Base Case scenario, to around 40% for the IRENA 1.5°C scenario, followed by 50-60% for the DNV (2023) and IEA (2023) NZE scenario, and almost 100% for the Franz et al. (2022) scenario that assumed net zero emissions by 2050 and a CO_2 price of 780 €/tonne CO_2. The predictions also vary widely regarding the types of fuels deployed, but most studies see the largest share of alternative fuel energy supplied in the form of ammonia IEA (2023), IRENA (2021), ABS (2020), and Franz et al. (2022) (scenario C assuming 780 €/tonne CO_2). Only the study by DNV (2023) predicted a slightly larger share than ammonia to be supplied from biofuels.

The fraction of fuels for the year 2050 varies even more widely, with the ABS (2020) Base Case scenario predicting less than 50% of fuel energy to come from zero or near-zero GHG emission fuels, whilst it can be noted that, in order to achieve coherence across the studies, LPG and LNG were classified as conventional fossil fuels by the authors of this literature review. All other studies, i.e. IEA (2023), IRENA (2021), DNV (2023) and Franz et al. (2022) (scenario C assuming 780 €/tonne CO_2) predicted alternative fuel shares between 75% and 100% by the year 2050. The highest share of fuel energy in these studies was predicted to be supplied in the form of ammonia, varying from around 40% to a 100% share.

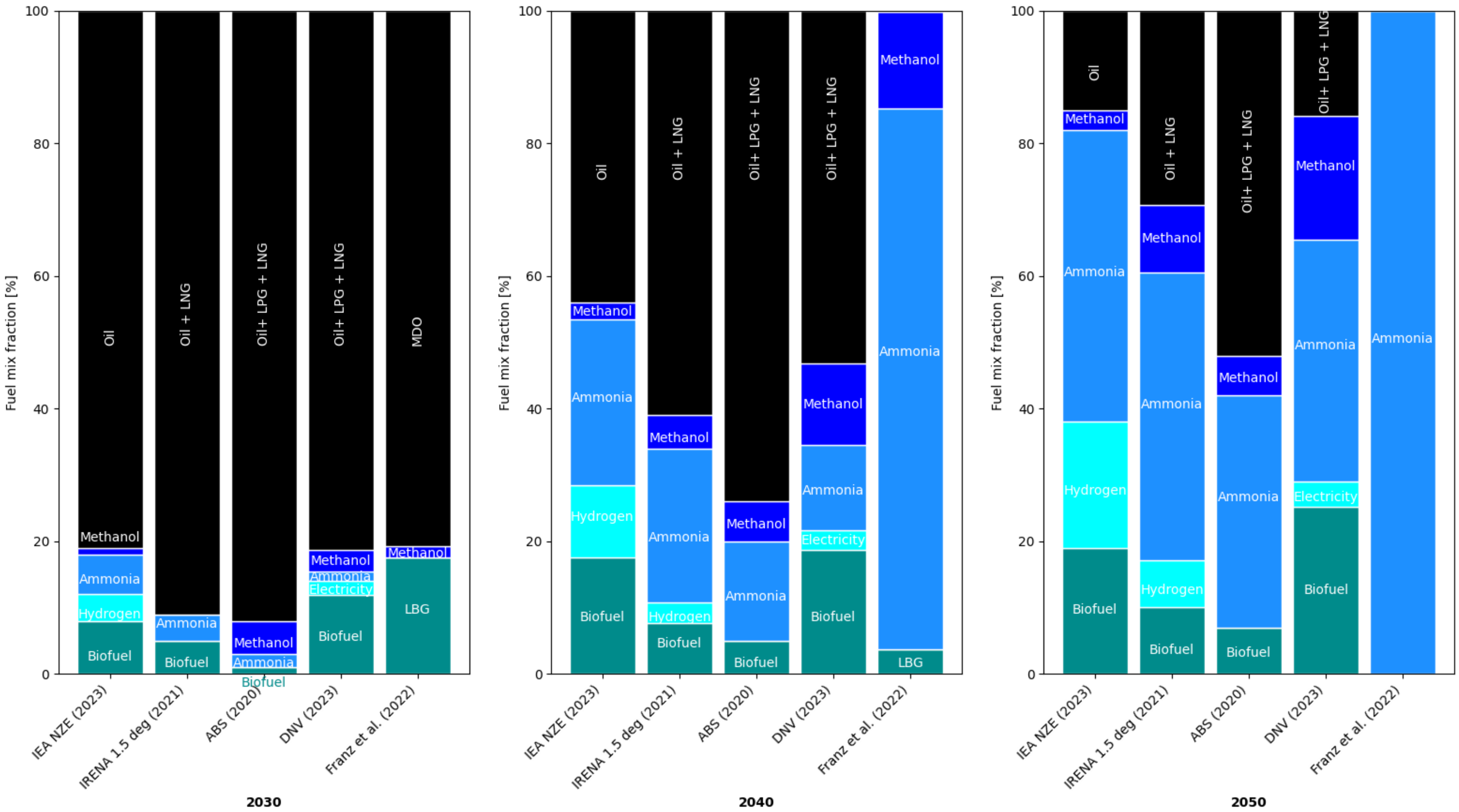

Figure 12. Projections of future fuel energy fractions by type for the years 2030, 2040, and 2050 (in % of total)

A number of studies (ABS, 2020, IRENA, 2021, Franz et al., 2022; DNV, 2023, and IEA, 2023) also try to calculate the absolute amounts of fuel energy necessary to meet future fuel demand. The absolute fuel energy requirements from international shipping reported by IEA (2023), IRENA (2021), ABS (2020), DNV (2023), and Franz et al. (2022) (scenario C assuming 780 €/tonne CO_2), have been summarised in figure 13. For the work of Franz et al. (2022) scenario C was chosen since this was the only one meeting the IMO GHG Strategy requirement of net-zero GHG emissions around 2050. Figure 13 shows that biofuels are expected to have the strongest initial increase and reach total annual energy amounts of up to 3 EJ for international shipping by as early as 2040, according to DNV (2023). The share of hydrogen energy deployed will remain relatively low at around 1-2 EJ for the years 2040 to 2050. The amount of energy supplied in the form of methanol is expected to reach around 1 EJ for the years 2040 to 2050 by most studies, whilst DNV (2023) predicts the highest amount of around 2.7 EJ in 2050.

All studies agree that by the year 2050 a total quantity of 3-5 EJ of fuel energy will be supplied to shipping in the form of ammonia[2]. In the year 2040 the predictions vary widely between 1-4 EJ of ammonia energy supplied to shipping.

In order to account for the varying calorific value of conventional and zero- or near-zero GHG emission fuels, the total mass of these fuels was visualised in figure 14. It can be seen that the expectations for the future mass of ammonia are about the same as the current mass of fossil fuels (around 200 Mtonnes of fossil fuels) used in international shipping, at a predicted mass of around 200 Mtonnes of ammonia in the year 2050.

All studies, bar DNV (2023), predict annual mass consumption of biofuels and methanol to remain below 50 Mtonnes up to the year 2050.

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2 While most studies seem to assign an important role to ammonia among the alternative fuels at hand, its absolute levels of energy seem to be inflated, particularly because Franz et al. (2022) 2050 prediction and DNV 2040 prediction introduced the highest weight.

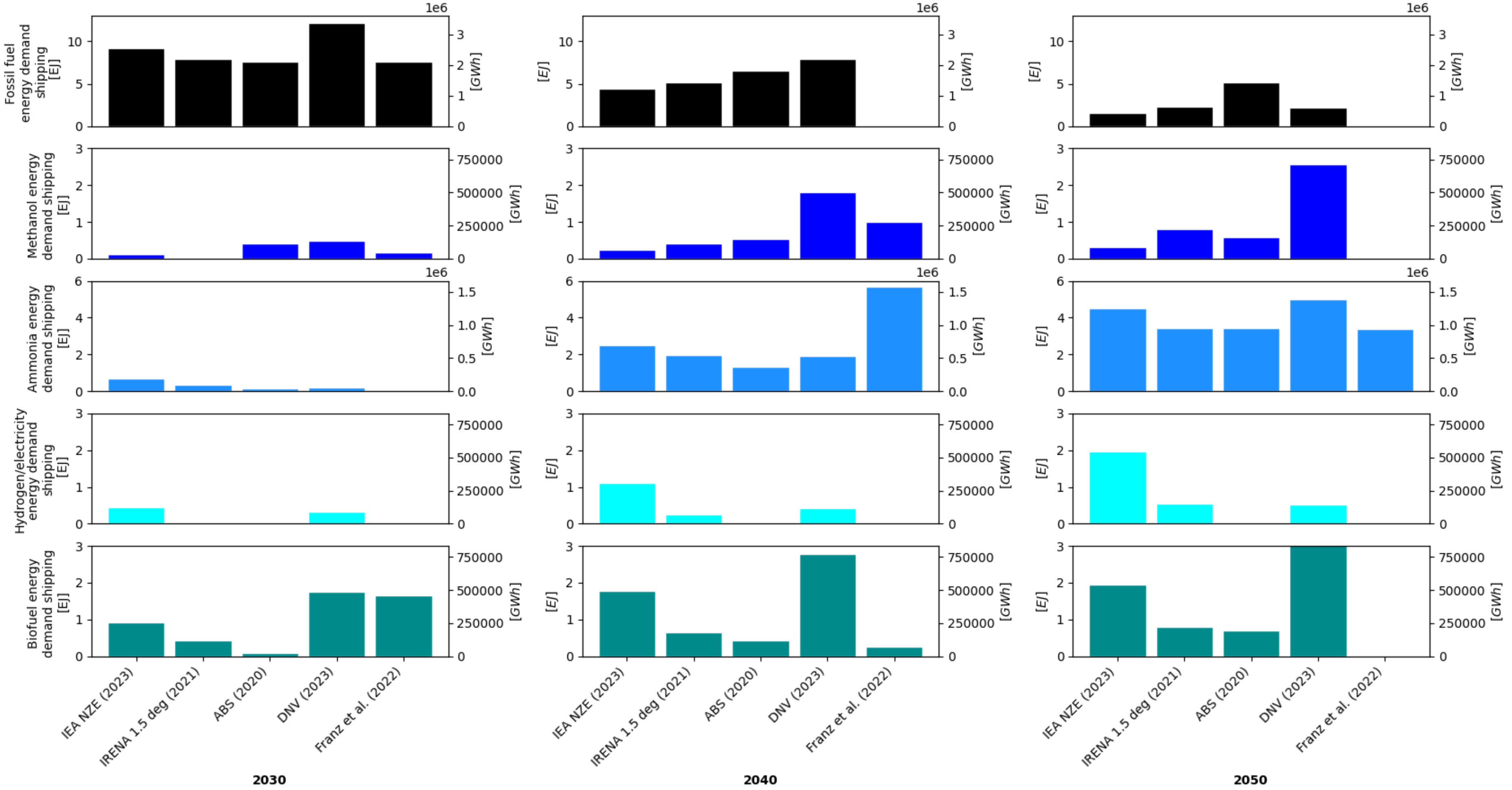


Figure 13. Projections of absolute future fuel energy requirements by type for the years 2030, 2040, and 2050 (in EJ and GWh)

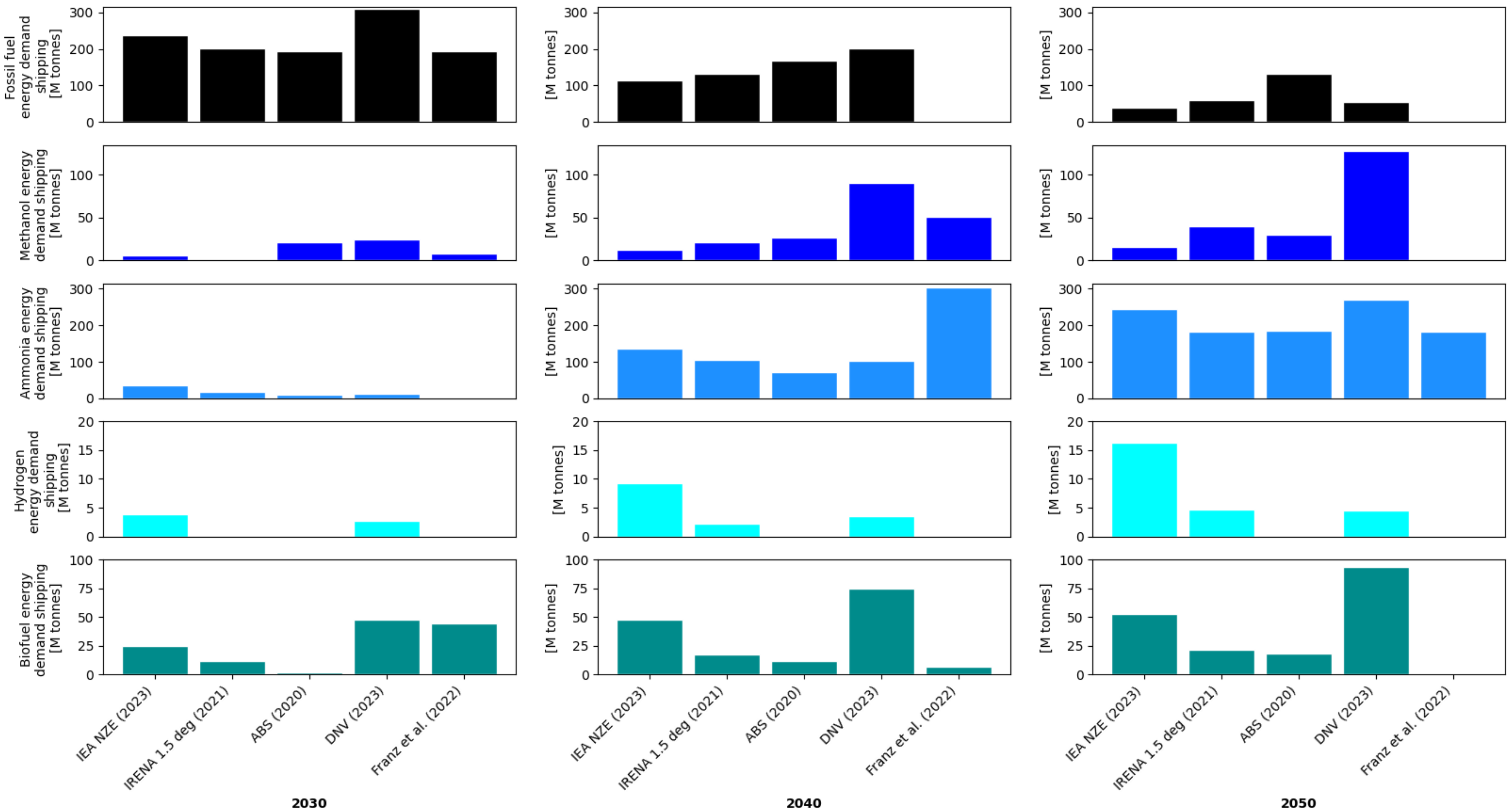


Figure 14. Projections of absolute future fuel mass requirements by type for the years 2030, 2040, and 2050 (in Mtonnes)

The fuel production costs, and the total potential for fuel production are important indicators for the economic impact of alternative fuel use. The fuel production costs have been reported by the Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (2021), IRENA (2021) and Lloyds Register & UMAS (2021), as shown in figure 15. The alternative fuel costs may be compared with estimates for conventional fuels such as LSFO 8-13 $/GJ in 2030 (LNG 6-10 $/GJ) and LSFO 4-17 $/GJ in 2050 (LNG 3-14 $/GJ). According to figure 15, alternative fuel production costs are expected to decrease by 2050, most likely as a result of technological advancements and higher maturity. However, the cost predictions also vary, as can be seen in Figure 15. For example, the cost-prediction for biofuels by Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (2021) decreased over the years 2030-2050, whilst that from Lloyds Register & UMAS (2021) increased. This was reported to be due to the expected increasing utilization of biomass sources, high demand for biofuel as drop-in fuel and the concurrent scarcity of this resources. Whilst it is unclear from the literature exactly why the predictions for total energy and mass supply by fuel (Figure 13 and Figure 14) differ between the scenarios, costs are likely to be an important factor in this.

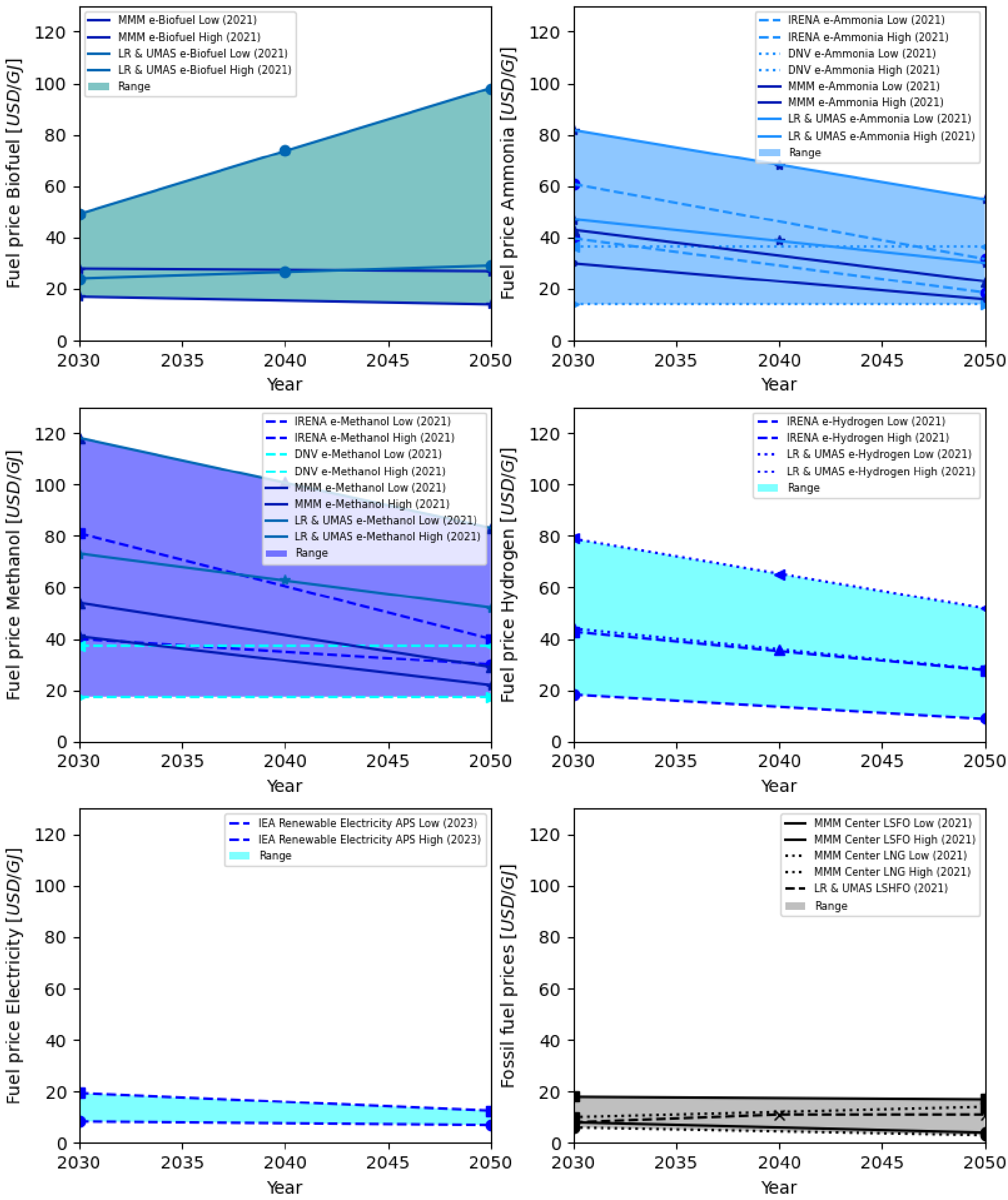


Figure 15. Projections of future fuel production costs by type for the years 2030 and 2050 ($/GJ)

The data shows that the lowest range of alternative fuel production costs are expected to be those for hydrogen, followed by ammonia in 2050. The cost predictions vary widely though. This can be attributed to, inter alia, the market maturity and competition of fuels, which can greatly impact the cost prediction. Hydrogen, for example, has been studied extensively and production methods are well established. Additionally, this can also be attributed to the sources available for each fuel. Sources available indicate a broader range of technological approaches and advancement. In the case of hydrogen, for example, there are multiple methods of production (such as steam methane reforming, electrolysis using renewable energy, etc.), each with its own cost dynamics and uncertainties. Furthermore, the supply chain infrastructure can contribute to the fuel cost and maturity. This infrastructure influences the simplicity of production, distribution, and ultimately the cost predictions linked with each fuel. Last but not least, feedstock availability pricing has also an impact on production cost. The study by Lloyds Register & UMAS (2021) predicted increasing prices for biofuels resulting from supply constraints and lack of sustainable biofuels. Hydrogen can be produced from various sources including natural gas, biomass, and water, while ammonia production principally relies on hydrogen derived from natural gas or renewable sources. Oscillations in feedstock availability can introduce variability in cost predictions for both fuels.

An outlook on the world's total primary energy supply and the final energy consumption of shipping is useful to see how the energy demand of shipping can be met by clean energy sources. Figure 16 shows final energy demand projections for shipping in the context of global primary energy supplies.

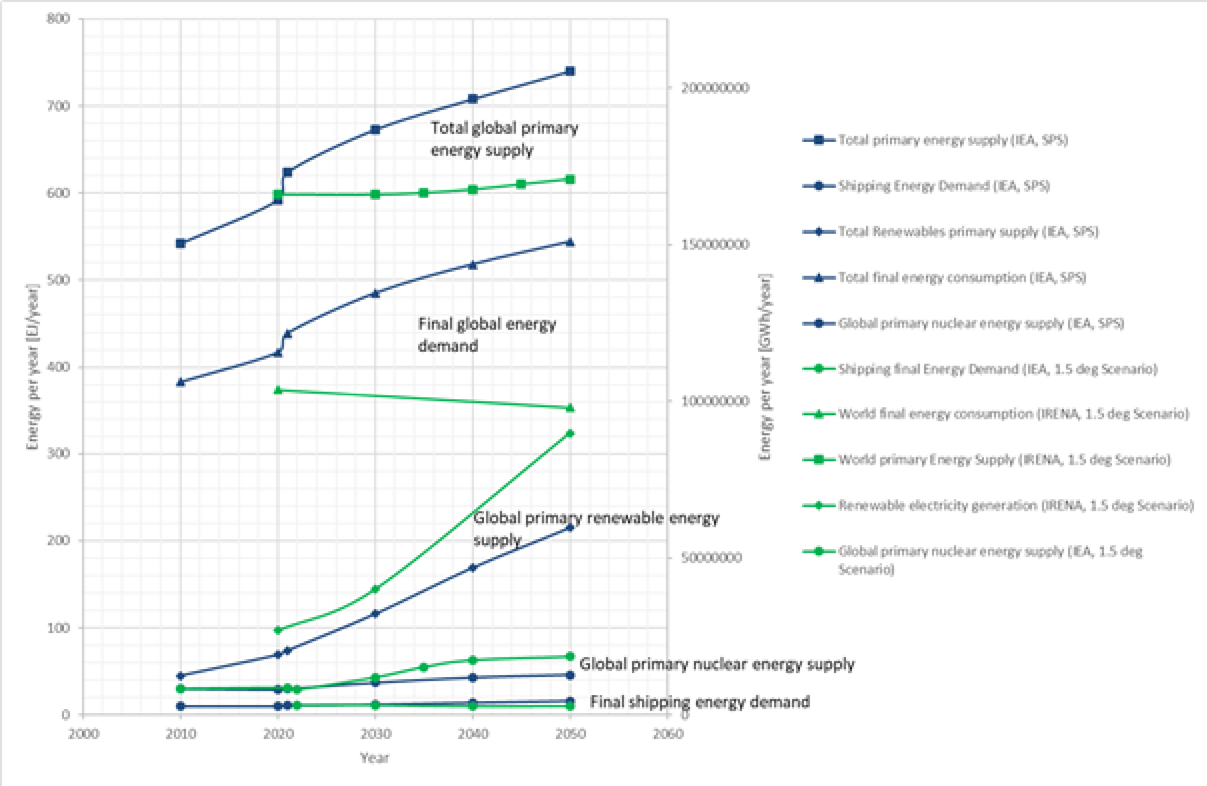


Figure 16. Projections of final shipping energy demand in the context of global primary energy supply and global primary renewable and nuclear energy supplies

The projected supply of individual fuels, such as hydrogen, bio-methanol, and bio-oils in the context of the final shipping energy demand and global renewable energy supply is shown in figure 17. The figure shows that primary renewable energy supplies far outreach the demand for energy from shipping. This is reinforced further in figure 18, which shows on a logarithmic scale the technical potential for various renewable energy sources along the projected final energy demand from shipping.

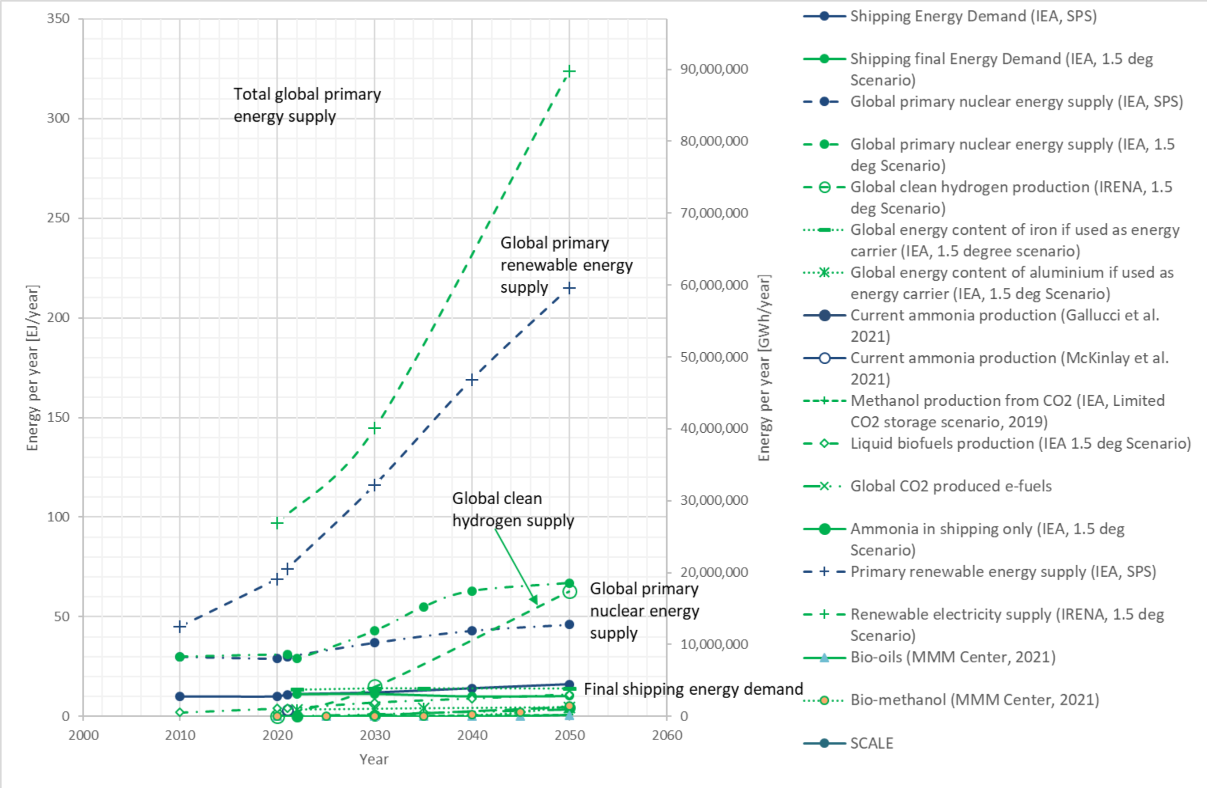


Figure 17. Projections for energy supplies renewable energy, hydrogen, bio-methanol and bio-oils

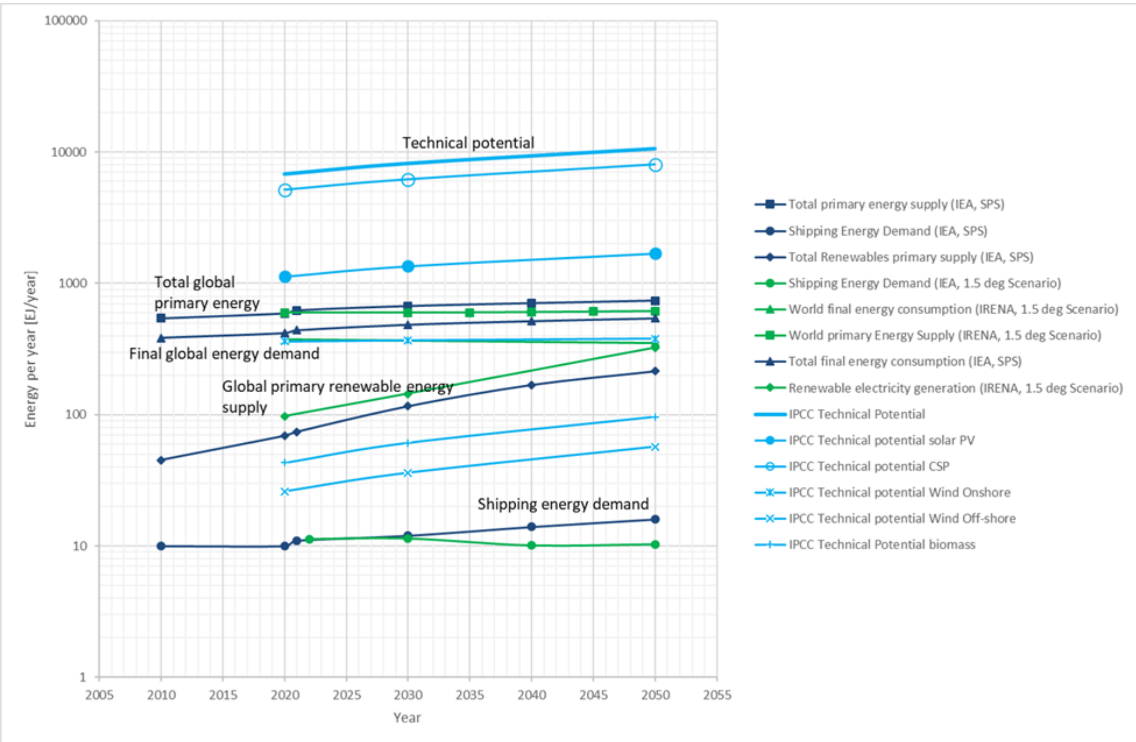


Figure 18. Projections of technical potential for various renewable energy types and final shipping energy demand

3.2 Results for subtasks 4 to 5

This section provides the comprehensive outcomes of a literature review on subtasks 4 to 5. Examination of various sources synthesized relevant information, resulting in a condensed overview of key findings.

3.2.1 Maritime costs – Determinants and impacts of increases

The first objective of this exercise was to review the literature with a view to finding some consensus as to the determinants of maritime transport costs. This was performed with a focus on developing countries, SIDS and LDCs[3].

It is important to note that for studies focusing on specific regions, products, or ship types/routes, the scope and relevance may be limited by the particular contexts they examine. However, these case studies offer valuable insights into the complex dynamics of maritime transportation under different conditions. The literature indicates that transport costs are an influential factor in determining a country's ability to participate in international trade. The countries that incur higher transportation costs face adverse consequences in terms of their economic growth. This review has concluded that the determinants of maritime transport costs from a maritime carbon pricing measure identified by Rojon et al. (2021) in figure 19 are an accurate reflection of research to date. The cost drivers were primarily derived from Rojon et al. (2021) insights. The article analyses the consequences of incorporating maritime carbon pricing into maritime transport costs. particularly in developing nations, SIDS and LDCs, while acknowledging the possibility of additional effects. It has investigated maritime transportation costs' significance, function and influence on trade and economic progress, emphasizing the situation in developing countries. Furthermore, it has pinpointed the potential effects of implementing a carbon price on maritime freight and its associated costs.

A complex interplay of geographical and operational factors influences the cost dynamics of maritime transport. Distance is a factor in ocean freight costs, with a 14-30% cost increase for each doubling of distance. Economic distance, defined through maritime connectivity and

[3] Developing economies have been defined as all economies classified as low, lower-middle, or upper-middle income countries by the World Bank (2024). LDCs and SIDS have been identified based on the lists maintained by the United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries, and Small Island Developing States (UN-OHRLLS, 2024).

global positioning, is greater than the impact of geographic distance alone. Location within the maritime network has a greater influence on transport costs than geographical distance. Improving centrality in the network is an effective strategy for reducing transportation costs.

Operational costs in ship running are influenced by vessel type and size choices, fluctuating bunker fuel prices, crew-related expenses and maintenance costs. The nature of the shipped product, including cargo type and volume, adds complexity to handling requirements and overall transportation costs.

Market-specific factors (which mainly pertain to aspects such as market segment, market size, trade imbalances, competition, market regulation, and the performance of the logistics sector), port infrastructure quality, and ease of access to other modes of transportation impact shipping demand, pricing and overall logistics costs. Strategic measures such as technological investments, route optimization, environmental compliance and risk management are significant challenges required for the optimisation of maritime transport costs. While this literature review focused on the influences mentioned above, the study did not identify any significant additional factors.

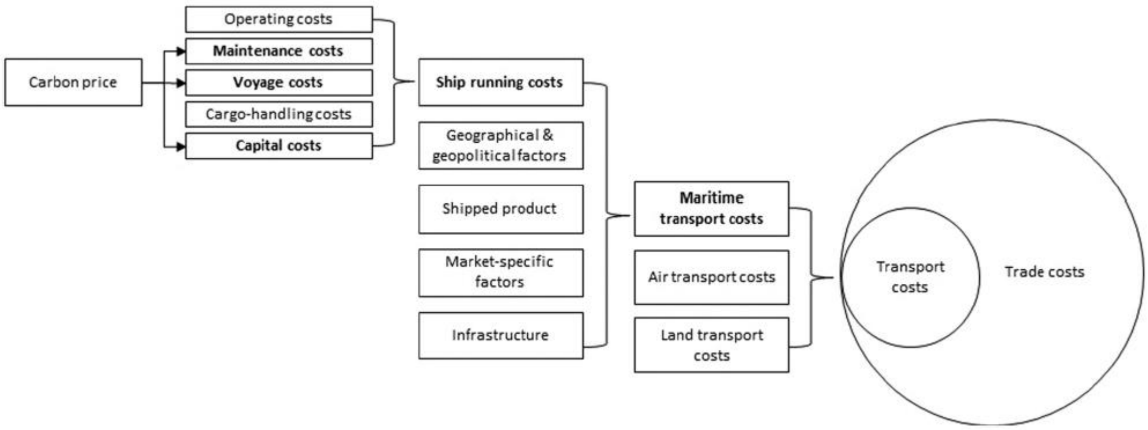


Figure 19. Impact of a carbon price on the determinants of maritime transport costs. Source: Rojon et al., 2021.

The literature indicates that, depending on the chosen input assumptions (transport segment and/or product studied, level of fuel and carbon price), the introduction of a carbon price on maritime transport could increase freight costs by between 0.4% and 16% (see table 3). Various studies have been undertaken to evaluate the diverse impacts associated with the introduction of a maritime carbon price on both maritime transport costs and the prices of imported goods. Table 3 provides a summary of these studies.

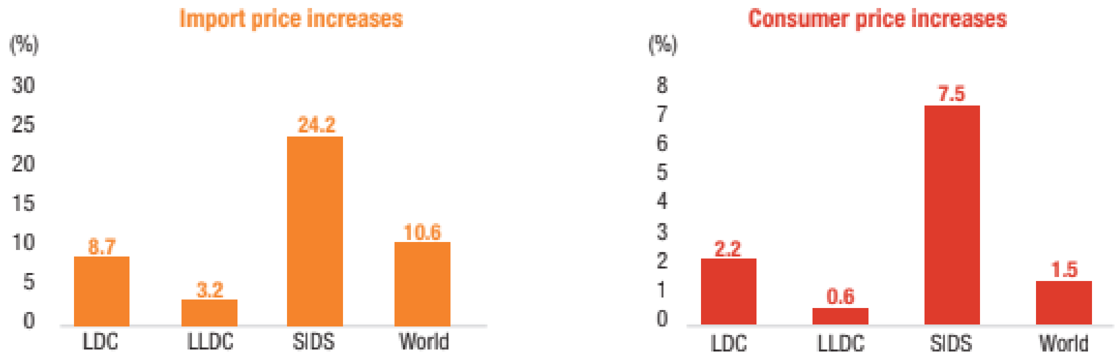
Most studies reviewed seem to concur that the potential increase on imported goods would be approximately 10% or lower. Furthermore, most studies reviewed indicate that the impact on import prices is forecast to be relatively small; lower than 1% in general[4].

Table 3. Overview of key findings from existing studies on the impacts of a maritime carbon price on maritime transport costs and the price of imported goods. Source: Rojon et al. 2021

Inputs/assumptions			Findings	
Specific focus, if any	Fuel price assumption	Carbon price or bunker contribution	Increase in Maritime transport costs	Increase in import prices of goods
Carbon price		US\$2.4–14.2/tCO_2 (2020); US\$6.6–38.8 (2050)	Not specified	0.00% (food & drink, agricultural products)
ETS		US\$56/tCO_2 (2020); US\$1022/tCO_2 (2050)	Not specified	0.00–0.08% (food & drink) 0.00% agricultural products
	US\$700/tonne	US\$30/tCO_2	4–8%	< 1%
	US\$450/tonne		6–12%	
Container shipping; select commodities	US\$550/tonne	US\$45/tonne fuel (US\$14/tCO_2)	1–5%	0.15–1.86%
Handy- and Capesize bulker,	US\$360.5/tonne	US\$30/tCO_2	7–16%	0.4–3%
Handysize product tanker, VLCC, container and ro-ro		US\$15/tCO_2	4–8%	0.2–1.4%
		10% increase of bunker fuel price	Not specified	< 0.2% (similar for exports)
Iron ore			5–14%	
Crude oil			1.2–6%	0.2–0.4%
Grains			2.5%	0.2–0.7%
Furniture & clothing				< 0.2%
Coking and steam coal		10% increase in spot bunker price	10–11%	
all, but impacts only determined for US	US\$2.40/gallon (~US\$741/tonne)	US\$15–30/tCO_2	Not specified	0.1–0.28%
Agriculture (only US)				0.14–0.29%
Raw material (only US)				0.18–0.36%
Crude oil (only US)				0.06–0.13%
Manufacturing (only US)				0.1–0.2%
all	US\$738/tonne	US\$10–50/tCO_2	0.4–3.4%	
all	US\$25/barrel (~US\$184/tonne)	Fuel price increase to US\$75/barrel (~US\$551/tonne)	1.49%	
		US\$18/tCO_2	Not specified	0.2%
Danish maritime cargo sector		US\$387–443/tCO_{2e}	100%	6–8%

Concerning containerised goods, figure 20 illustrates the relative impact of increases in container freight rate on both import and consumer prices. The graph highlights the dynamics between the rise in container freight rate and their repercussions on the costs incurred by both importers and consumers. It also illustrates the interconnectedness of freight rate adjustments and their cascading effects on overall economic considerations, providing valuable insights into the complex dynamics within the global trade landscape.

4 Higher impacts are expected for commodities with a low value per unit of mass or volume.

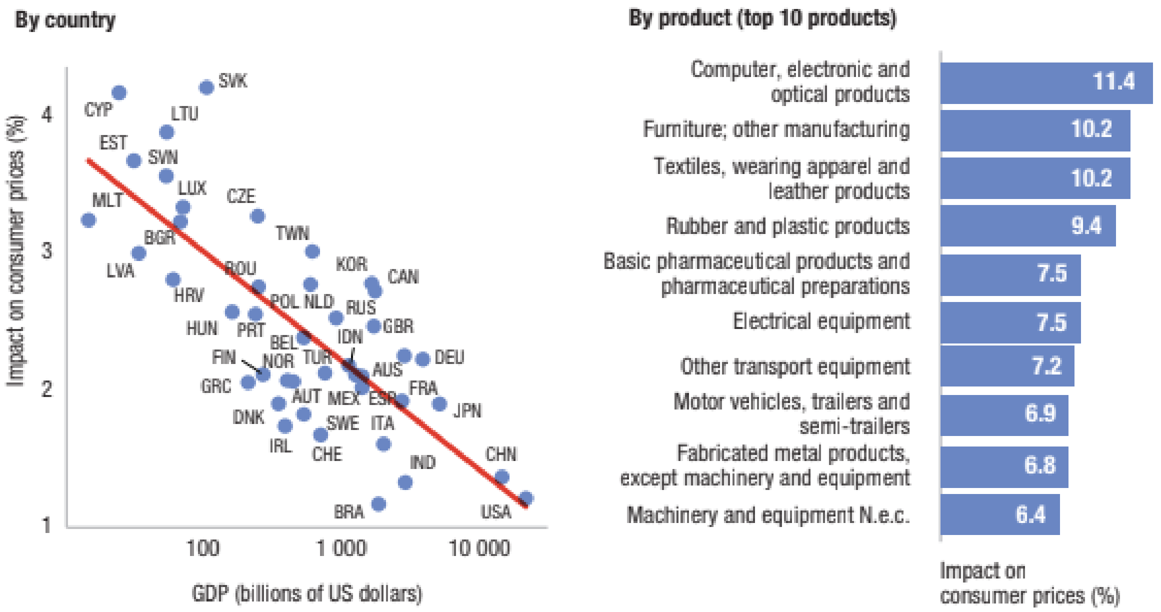


Sources: UNCTAD calculations based on data provided by Clarksons Research, *Shipping Intelligence Network* (accessed 2 September 2021), the IMF, *International Financial Statistics* and *Direction of Trade Statistics* (accessed 1 June 2021), UNCTADstat (accessed 1-2 June 2021), and the World Bank, *World Integrated Trade Solution* (accessed 2 June 2021) and *Commodity Price Data* (The Pink Sheet, accessed 23 August 2021).

Note: Scenario with a 243 per cent freight rate increase compared to no freight rate increase (i.e., same freight rate level as August 2020) as a percentage of the import or consumer price level. The impacts of the container freight rate surge on prices are based on a 243 per cent increase in the CCFI between August 2020 and August 2021. See technical note 1 for the detail of the methodology.

Figure 20. Simulated impact of current container freight rate surge on import and consumer price levels. Source: UNCTAD, 2021

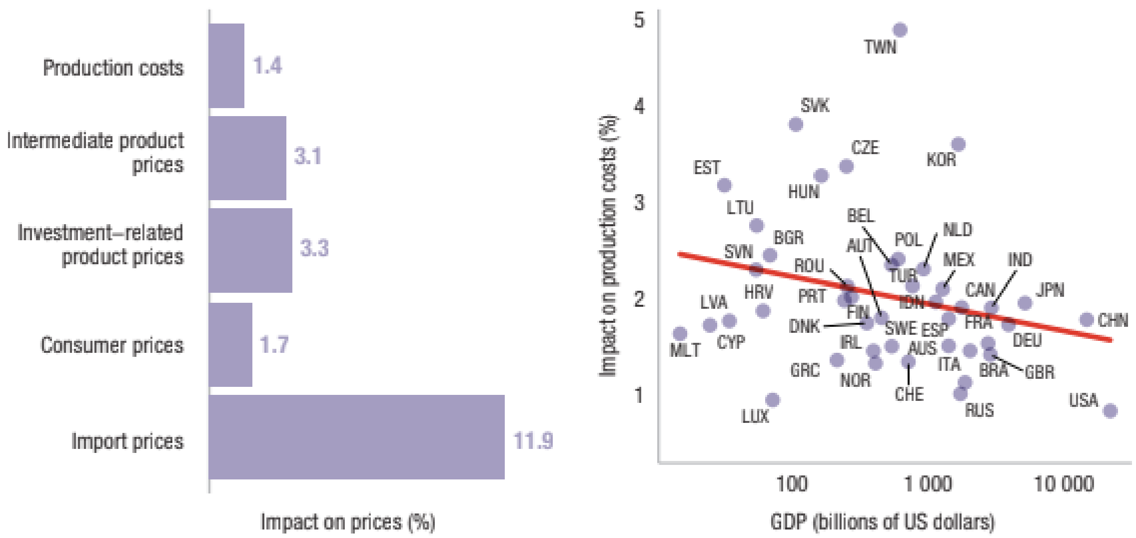
A comprehensive analysis of the repercussions resulting from increases in freight rates is depicted in both figure 21 and figure 22 by UNCTAD (2021). This underscores the pivotal role of structural factors in shaping transportation costs, including the quality of port infrastructure, the trade facilitation environment, and shipping connectivity. These elements contribute to the observed effects of freight rate increases and present opportunities for significant improvements. The data presented in figures 21 and 22 also illustrate the dynamics in global trade and their multifaceted impact on consumer prices across different countries and product categories.



Sources: UNCTAD calculations based on the WIOD (accessed 7–8 June 2021) developed by Timmer et al., 2015, Clarksons Research, *Shipping Intelligence Network* (accessed 2 September 2021), UNCTADstat (accessed 24 June 2021), and the Centre d'Études Prospectives and d'Informations Internationales, *Gravity Database* (accessed 21 May 2021).

Note: The impacts of the container freight rate surge on prices are based on a 243 per cent increase in the CCFI between August 2020 and August 2021. The simulated impacts on price levels are long-term impacts, i.e., the simulation assumes that the current container freight rate surge and the corresponding increases in production costs are fully passed to consumers. See technical note 2 for the detail of the methodology.

Figure 21. Simulated impacts of the container freight rate surge on consumer price levels, by country and by product. Source: UNCTAD, 2021

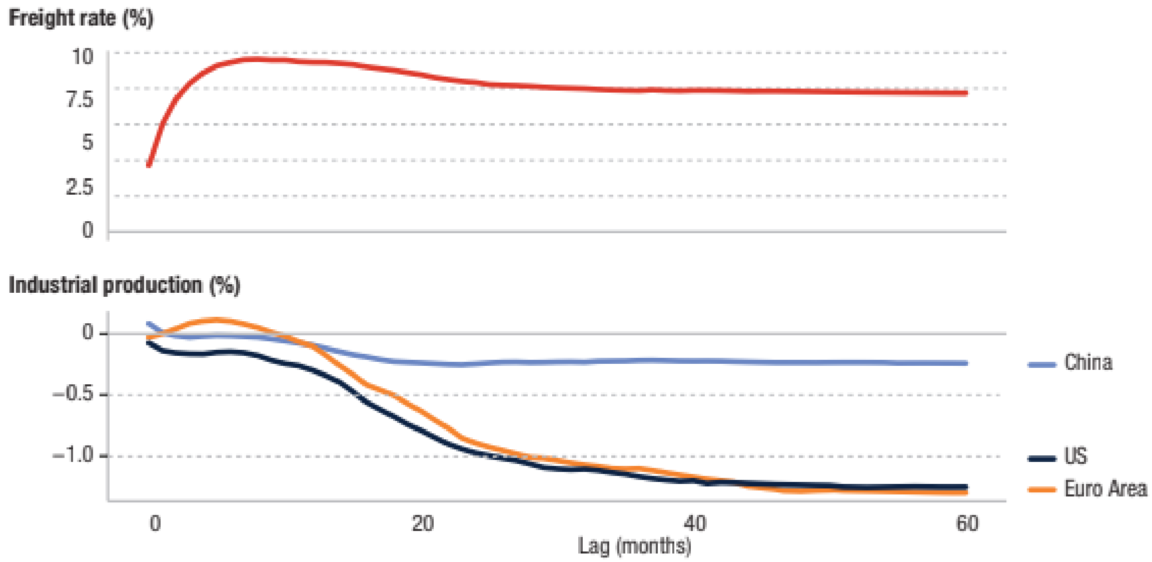


Sources: UNCTAD calculations based on the WIOD (accessed 7-8 June 2021) developed by Timmer et al., 2015, Clarksons Research, *Shipping Intelligence Network* (accessed 2 September 2021), UNCTADstat (accessed 24 June 2021), and the Centre d'Études Prospectives and d'Informations Internationales, *Gravity Database* (accessed 21 May 2021).

Note: The impacts of the container freight rate surge on price levels are based on a 243 per cent increase in the CCFI between August 2020 and August 2021. The simulated impacts on price levels are long-term impacts, i.e., the simulation assumes that the current container freight rate surge and the corresponding increases in production costs are fully passed to final users (i.e., consumers and firms). See technical note 2 for the detail of the methodology.

Figure 22. Simulated impacts of container freight rate surges. Source: UNCTAD, 2021

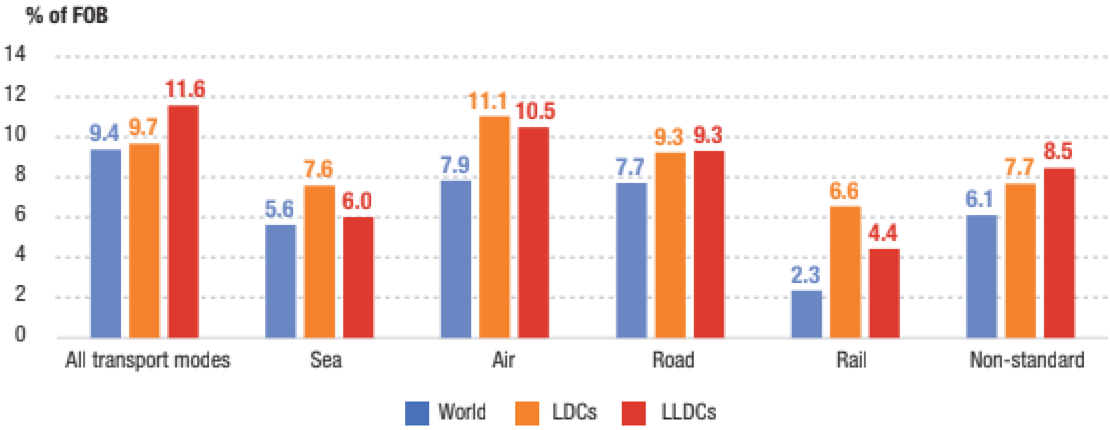
A comprehensive exploration of the impact on industrial production within major trading zones is illustrated in both figures 23 and 24. A simulation conducted by UNCTAD (2021) to investigate the impact of container freight rate on industrial production in the context of the COVID 19 pandemic, suggested a cumulative decrease of over 1% of industrial output is projected for both the United States and the Euro area, attributable to a 10% surge in container freight rates and concurrent disruptions in the supply chain. This projection is illustrated in figures 23 and 24. These figures highlight the possible consequences of heightened container freight rates and the effect of increased transport costs associated with importing goods.



Sources: UNCTAD calculations based on data provided by Clarksons Research, *Shipping Intelligence Network* (accessed 3 June 2021), the World Bank, *World Development Indicators* (accessed 10 June 2021), Bank for International Settlements, *Effective exchange rate indices* (accessed 10 June 2021), and Feldkircher et al., 2020 (accessed 10 June 2021).

Note: Global Vector Autoregression, consisting of 8 variables and 31 countries, is estimated using GVAR toolbox 2.0 (Smith and Galesi, 2014). Included endogenous variables for individual countries are the industrial production index, the consumer price index, the equity price index, the real effective exchange rate index, nominal short-term interest rates, and nominal long-term interest rates. Global variables are oil prices and container freight rates. See technical note 3 for the detail of the methodology.

Figure 23. Simulated dynamic impacts of container freight rate increase on industrial production. Source: UNCTAD, 2021



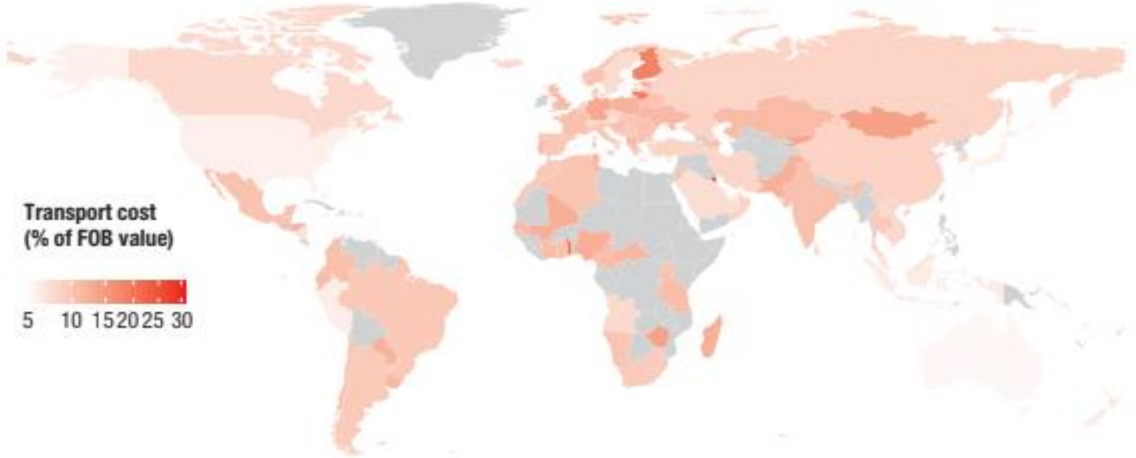
Source: UNCTAD calculations based on the GTCDIT developed by UNCTAD, the World Bank, and Equitable Maritime Consulting (accessed 24 June 2021).

Note: Transport costs of each transport mode are aggregated by group of importing countries. The aggregation is the sum of transport costs over all commodities, importing countries in the respective importing country group, and trading partners, divided by the corresponding sum of the trade value (in FOB), for commodities and country pairs for which both transport costs and FOB values are available.

Figure 24. Transport costs for importing goods by transport mode, world, LDCs, and LLDCs, 2016, percentage of FOB value. Source: UNCTAD, 2021

Figure 25 below highlights the problem of transport cost data availability, which is required for valid analysis of the potential challenges for SIDS and LDCs.

In terms of total imports, maritime transport accounted for 56% of the imports, surpassing the global average of 40%. This figure underscores the significant reliance of LDCs on maritime shipping for their imports, emphasizing the critical importance of accurate and comprehensive transport cost data for maritime transport.

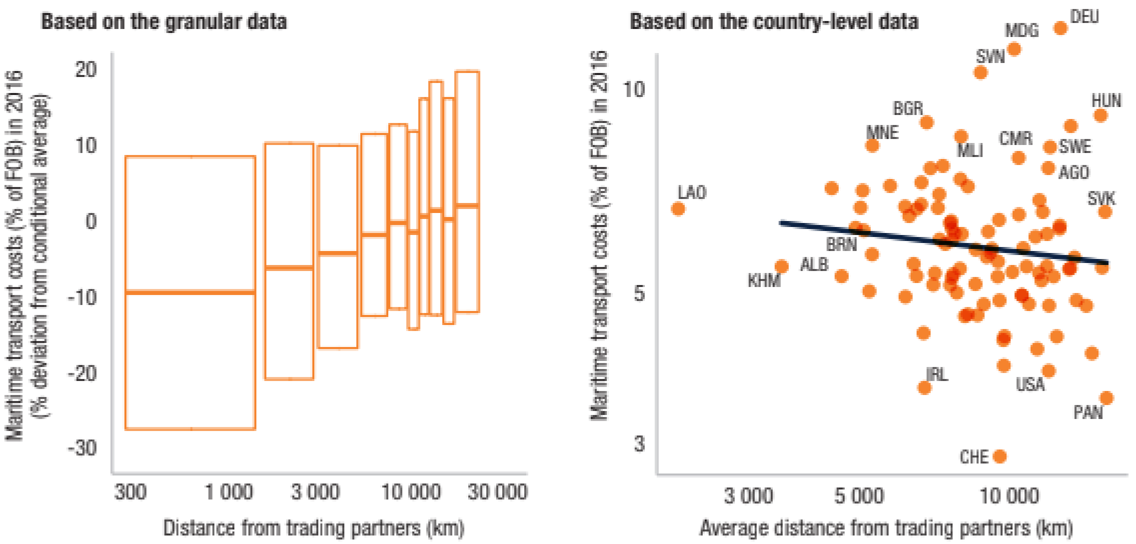


Source: UNCTAD calculations based on the GTCDIT developed by UNCTAD, the World Bank, and Equitable Maritime Consulting (accessed 24 June 2021).

Note: Grey colour indicates countries where import transport costs data are not available.
Transport costs are aggregated by importing country. Importers' maritime transport costs are summed up over all commodities and trading partners and, divided by the corresponding sum of the trade value (in FOB), for commodities and country pairs for which both maritime transport costs and FOB values are available.

Figure 25. Transport costs heatmap for importing goods, all modes of transport, 2016, percentage of FOB value. Source: UNCTAD, 2021

In ad valorem terms, smaller economies generally incur higher maritime transport costs, as illustrated in figure 26 by UNCTAD (2021). This fact may stem from factors such as insufficient liner shipping connectivity, poor port infrastructure quality, and deficient trade facilitation measures. These countries require an enhancement of their port facilities to facilitate improved shipping services, enabling the accommodation of larger vessels and reducing waiting times before port entry. Moreover, figure 26 offers insights into the complex relationship between shipping costs and their determinants. Expressly, an increase in shipping costs based on the distance between commercial partners is noted due to rising fuel and crew costs, even after considering factors such as product composition and local infrastructure. This trend is evident in the detailed breakdown of the data at the level of raw materials and bilateral countries. However, these nuances may need to be more noticeable in nationally aggregated data, where longer trade routes with lower transportation costs, such as those between the United States and China, may skew results due to larger trade volumes and economies of scale—rising from the use of larger ships for example.



Source: UNCTAD calculations based on the GTCDIT developed by UNCTAD, the World Bank, and Equitable Maritime Consulting (accessed 24 June 2021).

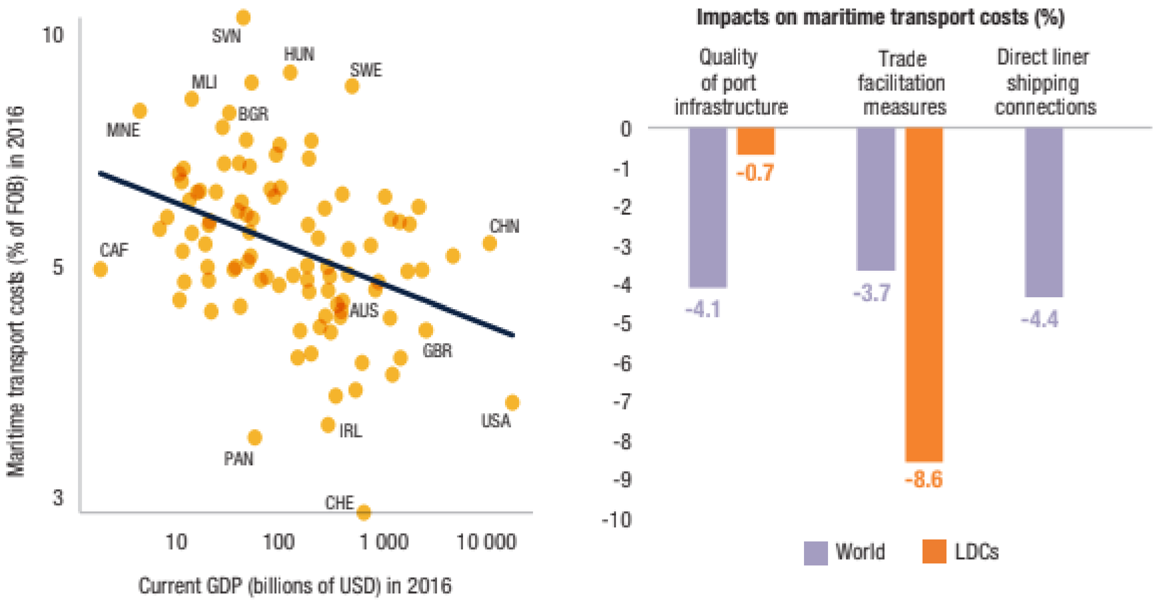
Notes: Left-hand side: The granular data is the bilateral trade data at the HS code 6-digit level. Distances from trading partners are divided into ten quantile groups. The y-axis shows the percentage deviation of maritime transport costs from their conditional average based on commodities and trading partners (obtained as residuals from a regression of maritime transport costs (as percentage of the FOB value) on commodity dummies and trading partner dummies). The boxplot shows the 25th percentile (lower line), median (middle line), and the 75th percentile (upper line) of maritime transport costs in each quantile group.

Right-hand side: Importers' maritime transport costs are summed up over all commodities and trading partners and, divided by the corresponding sum of the trade value (in FOB), for commodities and country pairs for which both maritime transport costs and FOB values are available.

Figure 26. Maritime transport costs for importing goods and distances from trading partners. Source: UNCTAD, 2021

Maritime transport costs, particularly in containerized trade, are influenced by bilateral trade imbalances. Specifically, when voyaging from high-demand to low-demand countries, numerous vessels often return with empty containers. This practice results in elevated shipping costs as it seeks to offset a portion of the ballast sailing expenses incurred during the return journey. Other factors can mitigate the impact of trade imbalances on maritime transport costs. Increasing cargo volumes to achieve economies of scale, for instance, has the potential to reduce maritime transport expenses. This is illustrated in figures 27, 28 and 29.

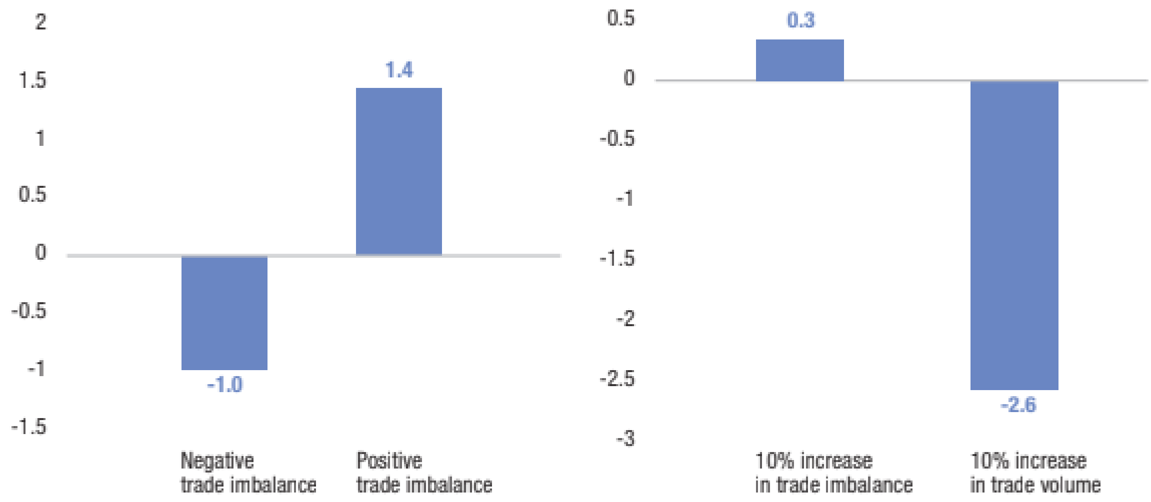
The data presented in figure 27 illustrates the impact of enhancing the highlighted factors, specifically improving them from their 25th percentiles to 75th percentiles. If the quality of port infrastructure is enhanced, there will be a 4.1% reduction in the average maritime transport costs worldwide. Similarly, better trade facilitation measures will lead to a 3.7% decrease in costs while improved liner shipping connections will result in a 4.4% decrease. In the case of LDCs, the greatest benefits would be derived from better trade facilitation, resulting in an 8.6% decrease, compared to a 0.7% decrease achieved by improving port infrastructure.



a) Maritime transport costs for importing goods, by country and size of economy

b) Impact of structural determinants on maritime transport costs for importing goods

Figure 27. Maritime Transport costs and impacts of structural determinants. Source: UNCTAD, 2021



Source: UNCTAD calculations based on the GTCDIT developed by UNCTAD, the World Bank, and Equitable Maritime Consulting (accessed 24 June 2021).

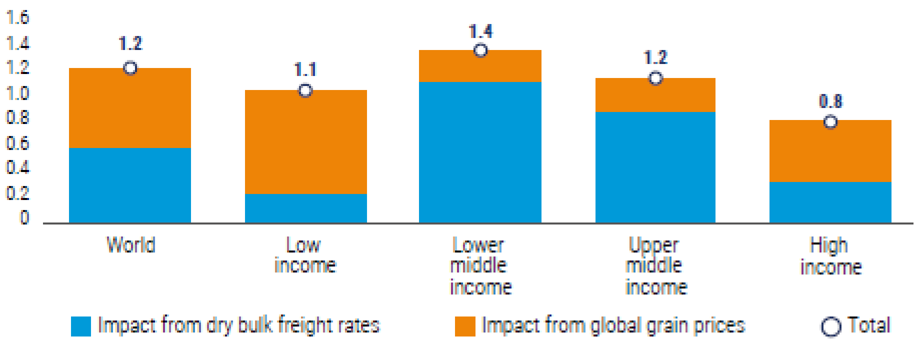
a) Maritime transport costs by direction of the trade imbalance

b) Impacts of trade imbalance and trade volume on maritime transport costs

Figure 28. Maritime Transport costs and impacts of trade imbalance. Source: UNCTAD, 2021

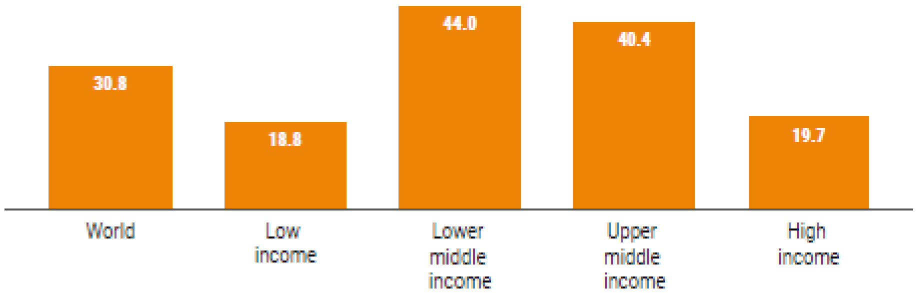
A simulation conducted by UNCTAD (2022) suggests that an increase in grain prices and dry bulk freight rates could result in a 1.2% rise in consumer food prices, as depicted in figure 29. As illustrated in figure 30, the magnitude of price hikes is anticipated to be slightly more pronounced in middle-income economies, where reliance on dry bulk shipping for food imports is higher, while for high-income economies the impact is smaller. Moreover, figure 26 offers insights into the complex relationship between shipping costs and their determinants. Expressly, an increase in shipping costs based on the distance between commercial partners is noted due to rising fuel and crew costs, even after considering factors such as product composition and local infrastructure. This trend is evident in the detailed breakdown of the data at the level of raw materials and bilateral countries. However, these nuances may need to be more noticeable in nationally aggregated data where longer trade routes with lower transportation costs, such as those between the United States and China, may skew results due to larger trade volumes and economies of scale—rising from the use of larger ships for example.

Conversely, low-income economies, with limited primary food processing capabilities, tend to import more processed foods, which typically arrives in containers, as indicated in figure 31. High-income economies, which have advanced technological capabilities, high quality and safety standards, and a type of consumer whose preferences fall on fresh foods, tend to import a more balanced mix of primary and processed food products than low-income economies.



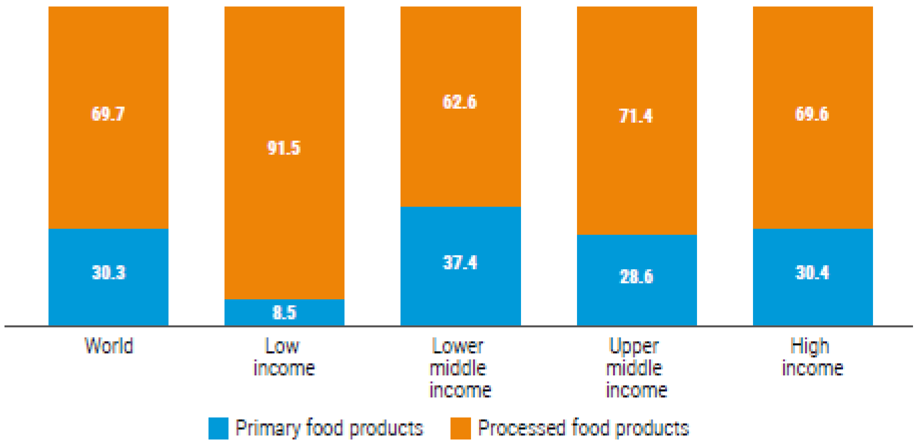
Source: UNCTAD calculations based on data provided by Clarksons Research, Shipping Intelligence Network, the IMF, International Financial Statistics, Direction of Trade Statistics and Consumer Price Index, UNCTADstat, and the World Bank, World Integrated Trade Solution, Commodity Price Data (The Pink Sheet) and A Global Database of Inflation[39] (accessed August 2022).[40]

Figure 29. Impact of higher dry bulk freight rates and global grain prices on consumer food prices, selected country groups (percentage). Source: UNCTAD, 2022



Source: UNCTAD calculations based on data provided by Sea/ (www.sea.live) and Food and Agriculture Organization, Food Balances.

Figure 30. Share of grains imported by bulk ships in total food imports, selected country groups, 2019. Source: UNCTAD, 2022



Source: UNCTAD calculations based on data provided by World Bank, World Integrated Trade Solution.

Figure 31. Share of primary and processed food products in food imports mainly for household consumption, selected country groups, 2020. Source: UNCTAD, 2022

Focusing on liquid bulk commodities, several factors and determinants influence the costs of maritime transportation.

Among liquid bulk cargoes, oil has a significant influence due to its large volume compared to chemicals and gas (Lun & Zhu, 2017). Expenses associated with shipping oil and gas commodities are influenced by factors such as loading costs, gross tonnage and operating costs (Sembiring & Sasono, 2018). Furthermore, the costs related to transportation are also impacted by the fiscal measures and risk management techniques utilized by companies in the oil and gas industry (Haushalter, 2000). Carriers specializing in the transport of liquefied natural gas (LNG) are affected by expenses such as daily handling costs, voyage costs, decommissioning costs and frequency of annual voyages (Zoolfakar et al., 2013). Disruptions in the futures of crude oil have significant influence on stock markets, indicating the interconnectedness between oil markets and financial components (Agnihotri & Chauhan, 2022). Moreover, the volatility manifested by oil markets affects non-energy commodity markets, such as bulk shipping (Lin & Chang, 2020).

Pereda et al. (2023) suggest that the introduction of a $50 per tonne of carbon dioxide equivalent (tCO_2eq) carbon levy could lead to a 7% reduction in shipping emissions. However, it is important to carefully consider the negative economic effects that may vary across countries, especially for middle- and low-income countries. These consequences could include a decline in both global exports and GDP. Additionally, the implementation of such a levy could exacerbate regional disparities, particularly in the energy, agriculture and mining sectors which would be most heavily impacted.

Wu et al. (2022) developed a model using trade volume to estimate carbon emissions and expenses in China's dry bulk shipping industry. China is responsible for 7% of global carbon emissions from dry bulk ocean freight. With carbon prices ranging from $100 to $300, the projected cost of the carbon fee for dry bulk shipping in China is $7.7 billion to $23.1 billion. This tax will significantly impact freight rates and trade prices for cargo.

Answer to research questions:

<u>Question: What are the factors of maritime transport that influence the costs associated?</u>

The factors influencing the costs associated with maritime transport are diverse and encompass both geographical and operational considerations. With regard to the determining factors of costs in maritime transport and their transmission within the maritime supply chain, the following is highlighted.

Geographical factors

- Distance plays a pivotal role in ocean freight costs, with a significant 14-30% cost increase for each doubling of distance (Rojon, 2021).
- Economic distance, which factors in maritime connectivity and global positioning, holds more influence than simple geographic distance. Location within the maritime network is a critical determinant of costs, surpassing the impact of geographical distance. Enhancing centrality in the network proves to be an effective strategy for reducing transportation costs (Wilmsmeier et al., 2009; Rojon, 2021). Wilmsmeier et al., 2009 address the problem of transport costs and their influence on food prices for South American imports.

Operational factors

- Operational costs in ship management are subject to the fluctuating prices of bunker fuel, vessel type and size choices, crew-related expenses and maintenance costs.
- The nature of the shipped product, including cargo type and volume, introduces complexity to handling requirements, impacting overall transportation costs (Rojon 2021).

Market-specific considerations

- Market-specific factors, encompassing regional economic conditions, port infrastructure quality and proximity to other modes of transportation, significantly influence shipping demand, pricing and overall logistics costs (IMO, 2020).

Strategic measures for cost optimization

- To address challenges and optimize maritime transport costs, strategic measures such as technological investments, route optimization, environmental compliance and risk management are deemed relevant (Baresic et al. 2022).
- Moreover, variables identified include possible carbon pricing mechanism, direct regulatory interventions, measures at the national or regional level as well as market barriers and failures in the maritime sector.

Impact of different factors on shipping costs

- Literature suggests that introducing a carbon pricing mechanism and direct regulatory approaches could reduce the competitive gap between fossil fuels and alternatives (Baresic et al. 2022). However, the diversity of barriers and market obstacles makes achieving the objectives of the 2023 IMO GHG Strategy through a single policy instrument uncertain.

Elements contributing to the analysis of cost pass-through in the maritime supply chain

- Cost pass-through within the supply chain is influenced by the implementation of a carbon pricing mechanism, direct regulations, actions at the national or regional level, and impacts resulting from increases in fuel costs on trade and GDP (Rojon et al. 2021). Based on the literature review conducted, it would be necessary to conduct thorough assessments on the chain effects that may arise from the above-mentioned factors.

Modes of cost pass-through in the maritime supply chain

- Cost pass-through is expected to focus on specific segments, with potential effects on shipping and trade costs but with less impact on prices of imported goods, especially in the cost of global trade (UNCTAD, 2023). Concerning potential effects above mentioned, for example the pass-through of costs on maritime shipping has an impact on freight rates and the impact on trade costs is that an increase in trade costs for the importing country results in a higher tariff rate being applied to imported goods.

<u>Question: How do various factors within maritime transport impact associated costs?</u>

Various factors within maritime transport significantly impact associated costs. The literature highlights multiple measures capable of narrowing the competitiveness gap between fossil fuels and zero or near-zero GHG emission technologies, fuels and/or energy sources. Among these, a carbon pricing mechanism and direct regulatory approaches stand out, but a hybrid approach is favoured due to the complexity of market barriers hindering the effectiveness of a single policy tool (Baresic et al., 2022).

The introduction of a carbon pricing mechanism demands a pricing instrument, usually tied to carbon, with the potential to generate revenue that can be reinvested in decarbonization efforts. Additionally, employing direct regulatory strategies, such as performance, technology and product standards, is effective, albeit less lucrative than a carbon pricing mechanism due to their inability to generate revenue.

National and regional measures are gaining traction, fostering niche markets for zero or near-zero GHG emission marine fuels (Baresic et al., 2022). They play a pivotal role in market creation and RD&D, contributing to closing the gap and establishing policies that benefit SIDS and LDCs.

Increases in maritime logistics costs can have marginal effects on global trade flows and GDP, projected at up to 1% of GDP, with less than 0.1% impact on global GDP. However, SIDS and LDCs may bear greater negative impacts due to their comparatively higher transport costs. For instance, SIDS face potential export reductions of 8% to 18% for every 10% rise in transport costs, with coffee exports being particularly sensitive (Rojon et al., 2021).

To address the challenges posed by climate change impacts on vulnerable States, careful consideration could be given to the potential allocation of revenues generated by carbon pricing mechanisms (Baresic et al., 2022). However, it is important to highlight that further research, specifically focusing on SIDS and LDCs, is important for a comprehensive understanding of the quantitative and qualitative effects of the proposed measures on shipping costs. The validity of outcomes in this domain heavily relies on access to reliable data.

<u>Question: What elements contribute to the cost pass-through analysis within the maritime supply chain? How does the pass-through of costs occur within the maritime supply chain?</u>

Elements contributing to the cost pass-through analysis within the maritime supply chain encompass a range of factors, as highlighted in the extensive literature review:

- **Policy measures and impact:** The evaluation of various mid-term measures, including a carbon pricing mechanism and direct regulatory strategies, plays a pivotal role. The selection of these measures affects ship running costs and impacts the overall cost structure within the maritime industry. For instance, carbon pricing mechanisms influence transport costs differently from import prices due to the broader spectrum of trade costs.

- **Maritime logistics costs:** Increases in maritime logistics expenses, projected at different levels (10%, 20%, and 50%), can lead to changes in global trade flows, albeit within a limited range of up to 1% (UNCTAD, 2023). However, despite its seemingly modest global impact on real GDP (less than 0.1%), these cost escalations could have more pronounced adverse effects on SIDS and LDCs due to their higher-than-average transport costs (Rojon et al., 2021).
- **Impact on export/import volumes:** The predicted rise in transport costs for SIDS, around 6% per unit, could result in significant reductions in export units, ranging from approximately 8% to 18% for every 10% increase in transport costs (Rojon et al., 2021). Commodities like coffee from SIDS exhibit heightened sensitivity to transportation cost fluctuations, with forecasts indicating a potential decline of 20-30% for every 10% increase in transport costs (Rojon et al., 2021).
- **Mitigation strategies:** To alleviate the impact on vulnerable regions like SIDS and LDCs, directing a substantial proportion of revenues generated from policy measures - carefully applied, such as through carbon pricing mechanisms, could serve as a mitigating mechanism (UNCTAD 2023).

This detailed analysis underscores the complexity of cost pass-through within the maritime supply chain and emphasizes the need for further research. Quantitative and qualitative assessments focusing on SIDS and LDCs are needed, necessitating reliable data for valid outcomes in understanding the comprehensive impacts of proposed measures on shipping costs and associated economies.

3.2.2 Review of initial assessments of candidate mid-term GHG reduction measures

This section provides an overview of the initial impact assessments submitted to IMO. The aim is to transmit the information previously provided transparently without incorporating any new analysis of the impacts of possible GHG reduction measures in the medium term. It is relevant to highlight that the proposal outlined does not encompass all current proposals currently under consideration.

In June 2023, UNCTAD published its Preliminary Expert Review of the technical and economic elements, and their possible combinations, of the proposals for candidate mid-term GHG reduction measures submitted to ISWG-GHG and MEPC (document MEPC 80/INF.39/Add.1).

A total of 26 submissions were reviewed by UNCTAD. These proposals for mid-term measures comprise technical and economic elements and their possible combinations. Table 3 provides a summary of the submitted proposals, together with their respective technical and economic elements as well as their revenue-generating potential.

Table 4. Mapping of the proposals[5]. Source: UNCTAD, 2023

Type of Measure	Proposal	Economic element				Technical element		Revenues					Scope of emissions covered
		Levy/ Fund/ Contribution/ Fee	Cap and Trade (ETS)	Feebate	FCUs/ SRUs/ GRUs / RUs	GFI	CII	Rewards	R&D	Capacity Building	Support for developing countries, SIDS, LDCs	Administration	
Economic measures	ISWG-GHG 13/4/1 (Norway)		X										TtW CO2 open to expand
	ISWG-GHG 15/3/7 (ICS)	X		X				X	X	X	X	X	First TtW then Wtw CO2 or GHG
	MEPC 76/7/12 (Marshall Islands and Solomon Islands)	X		X				X	X	X	X	X	WTW GHG
	ISWG-GHG 14/3/1 (Japan)	X		X				X	X	X	X	X	WtW GHG
Technical measures	ISWG-GHG 15/3/1 (Austria et al.)				X	X				X			WTW GHG
Basket of measures	ISWG-GHG 13/4/2 (Norway)		X			X				X	X	X	TtW CO2 open to expand
	ISWG-GHG 12/3/9 (Argentina et al.)	X		X			X	X	X	X	X	X	TtW CO2
	ISWG-GHG 14/3 (ICS)	X		X		X		X	X	X	X	X	First TtW then Wtw CO2 or GHG
	ISWG-GHG 13/4/11 (Marshall Islands and Solomon Islands)	X		X		X		X	X	X	X	X	WTW GHG
	ISWG-GHG 15/3 (Japan)	X		X		X		X	X	X	X	X	WtW GHG
	ISWG-GHG 15/3/2 (Austria et al.)	X		X	X	X		X	X	X	X	X	WTW GHG
	ISWG-GHG 15/3/4 (China)	X		X	X	X		X	X	X	X	X	WtW GHG

Each of the proposals should consider, inter alia, (1) geographic remoteness of and connectivity to main markets; (2) cargo value and type; (3) transport dependency; (4) transport costs; (5) food security; (6) disaster response; (7) cost-effectiveness; and (8) socio-economic progress and development. They should also indicate both positive and negative potential impacts and analyse the extent of the impacts (e.g. by costs, GDP, etc). Impact assessments should also assess whether the proposed measure is likely to result in disproportionately negative impacts and, if so, how these could, as appropriate, be addressed. Table 5 and table 6, from document MEPC 80/INF.39/Add.1, summarize the initial impact assessments and various proposals of mid-term measures.

5 A feebate system is a levy-based system that uses all or part of the revenues raised through the levy/fund/contribution to offer a rebate to first movers and reward ships that are built for and will utilize alternative marine fuels. GRUs/RUs FCUs/SRUs are also classified as economic elements when flexible compliance with GFI entails pricing of the FCUs.

Table 5. Summaries of initial impact assessments

ISWG-GHG 12/3/8 (ICS)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	The impact on geographically remote States would depend on the quantum of the carbon levy adopted. For a voyage of 1,100 nm, a levy of $100 per tonne of CO_2 would increase the price of iron ore in the import country by 4%, whereas a levy of $400 per tonne by 15.8%. For a voyage of 3,500 nm, a levy of $100 per tonne of CO_2, would increase the import price by 1.3% while a $400 per ton by 5.4%. This initial impact assessment therefore suggests that, for cost sensitive iron ore trades, a levy initially set at $100 per tonne of CO_2 or lower might be less likely to be viewed as having disproportionately negative impacts on States that are geographically remote from their markets than a higher levy amount, but arguably would not have significantly less impacts on geographically remote States than a levy which was set at a lower quantum than $100 per tonne of CO_2. The assessment also looks at price of delivered foodstuff. A levy of $100 per tonne of CO_2 would increase prices by 21% whereas a levy of $200 or $400 by 41% and 83% respectively. For a voyage of 5,800 nm, a levy of $100 would increase delivered prices of crude oil by 0.6% while a levy of $200 or $400 by 1.2% and 2.4% respectively.
Cargo value and type	Given that the prices on delivery of all the cargoes examined are volatile, generally speaking the delivery price impact of any of the levy quantum examined, up to and including $400 per tonne of CO_2, fell within the average monthly volatility of delivered cargo prices the during 2021. However (other than for container trades for which freight rates were exceptionally high during 2021) the impact of a levy of $100 per tonne of CO_2 on most trades would be to bring freight rates in these trades in the vicinity of their 10-year average, whilst a levy of $400 per tonne of CO_2 would bring freight rates in the vicinity of their 10-year peak.
Transport dependency	The proposed measure should not disproportionately impact States which are dependent on maritime transport and – by expediting the use of zero-carbon fuels that will make decarbonisation of the sector possible – it will allow these States to continue to enjoy access to low cost and efficient maritime transport whilst meeting the levels of ambition set by the Initial IMO Strategy (due to be revised by 2023) which will be particularly important for LDCs and SIDS.
Transport costs	The proposed measure should not significantly impact transport costs to an extent beyond those impacts in most trades which already result from significant volatility of fuel oil prices and variations in freight rates due to changes in supply and demand (plus unexpected developments such as the COVID-19 pandemic and the conflict in Ukraine). Moreover, programmes to be supported by the proposed IMO Fund could be designed to identify potential mechanisms for reducing the cost of transportation to LDCs and SIDS, and other geographically remote locations, whilst complying with existing and future regulations that require a reduction in carbon intensity.
Food security	The analysis above with respect to the impact on freight rates in dry bulk trades (iron ore and coal), which suggests that the impacts of the levy quanta examined generally fall within the average monthly volatility of delivered cargo prices, is equally applicable to bulk carriers which are used to move key food stuffs in bulk. With respect to the transport of

Table 5. cont. Summaries of initial impact assessments.

ISWG-GHG 12/3/8 (ICS)	
	containerized perishable cargoes, this assessment suggests that whilst a levy initially set much above $100 per tonne of CO_2 might be seen as having large impacts on the price of delivered perishable foodstuffs, when seen as a proportion of the delivered cargo price the impact will be significantly less in the context of the much higher freight rates experienced in liner trades since the middle of 2021.
Disaster response	No adverse impact on disaster response.
Cost-effectiveness	IMO Fund to help expedite the transition to zero-carbon emissions without any direct financial cost to States and with minimal administrative burden. The proposed levy-based economic measure is therefore considered to be a cost-effective measure which will help facilitate successful delivery of the 2050|levels of ambition set out in the Initial IMO Strategy.
Socio-economic progress and development	The proposal should have no adverse impacts on socio-economic progress and development. To the contrary, by assisting global decarbonization efforts it will contribute to socio-economic progress and development, consistent with the UN SDGs for 2030.

ISWG-GHG 13/4/6 (Japan)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	N/A
Cargo value and type	N/A
Transport dependency	N/A
Transport costs	It is indicated that the average increase in shipping costs is 3.8% for ($25/ CO_2 tonne), 7.6% for ($50/ CO_2 tonne), 15.3% for ($100/ CO_2 tonne), and 30.5% for ($200/ CO_2 tonne). The results were obtained from the estimated fuel cost share of shipping costs, which averaged 36.6% (ranging from 11.7% to 48.5%) for bulk cargo shipping and 27.1% (ranging from 0.5% to 60.1%) for container shipping. The impact of the mandatory contribution on shipping costs can be compared against the normal volatility of container freight rates, as had been done for assessing impacts of short-term measures on maritime logistics costs (see MEPC 76/7/13, annex, pages 14 to 15). For instance, the level of estimated increase in average shipping costs under the four scenarios seem to lie within normal volatility of container freight rates from China to South America before the COVID-19 pandemic (see Figure 5). The analysis assumes that payment is made by all ships and does not account for the changing fleet composition of fossil-fuelled ships and ZEVs. In other words, deployment of ZEVs which do not need to pay a mandatory GHG contribution is not considered in the model. (para 22, ISWG-GHG 13/4/6).
Food security	N/A
Disaster response	N/A
Cost-effectiveness	N/A

Table 5. cont. Summaries of initial impact assessments.

ISWG-GHG 13/4/6 (Japan)	
Socio-economic progress and development	N/A

ISWG-GHG 12/3/14 (Norway)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	N/A
Cargo value and type	N/A
Transport dependency	N/A
Transport costs	Consumers and end users will experience some increases in prices. The indications of the increases in the context, however, are based on the end users bearing all costs, and that the price surge on freights is representative for the measure discussed here. Under these assumptions, the indicated price increases are still relatively modest (e.g., 2% increase in consumer prices for SIDS). Given that some of this increase will likely be shared by shipowners, cargo owners and others in the supply chain, the costs increases are likely to be relatively modest for each involved.
Food security	Certain goods are of larger significance for people's welfare than others, and there are likely variations in how different industries/goods are affected (see Figure 24 in document ISWG-GHG 12/3/14). Prices for imported foods will likely increase, meaning that people critically relying on imported foods, also occasionally, could face reduces food security. Water transport costs make up a small part of the food industry demands (>0.5%), but the impact of the costs increases also depend on purchasing power of the consumers. This should be explored further in a comprehensive impact assessment.
Disaster response	The capacity and response times for responding to the measure has not been investigated. This will depend on the design of the cap-and-trade system.
Cost-effectiveness	N/A
Socio-economic progress and development	N/A

ISWG-GHG 12/3/4 (Austria, et al.)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	The study shows that the impacts created by a generalized GHG reducing policy (such as the GFS or others) are typically much less than a tenth of a percent for most countries and regions, although they vary across different types of economy. These figures exclude potential benefits from fuel exports, which have not been modelled. The results are the product of the interactions between carbon intensity of different transport modes and the potential for substitution, the relative balance between imports

Table 5. cont. Summaries of initial impact assessments

ISWG-GHG 12/3/4 (Austria, et al.)	
	and exports (and the respective trading partners for these), along with the consequent impacts on investment. Below, some of the results are presented and interpreted. Furthermore, higher transport costs may affect States that are far away from their main markets more significantly than States close to their main markets or better connected. On the other hand, States which have the capacity to produce and export renewable fuels will be positively impacted. The consequence of a generalized increase in transport costs depends on the country or region's circumstances. For nearby trading partners, the generalized increase in transport cost can result in substitution occurring and an increase in market share relative to more remote trading partners. The transport cost increase can also cause imports to be substituted with domestic production – therefore increasing investment in the country or region.
Cargo value and type	In general, higher transport costs may affect trade of low-value cargoes more negatively than high-value cargoes. Likewise, transport of specific types of cargo like perishable goods may be negatively affected when higher transport costs change for example optimal speeds. Considering this specific impact is also important from the perspective of ensuring food security, especially with respect to possible changes in import prices of essential food commodities, additional time or possibility to procure them.
Transport dependency	States that are highly dependent on maritime transport, e.g., to provide essential goods or services, are more likely to be affected more significantly by changes in shipping costs than States which have a lower transport dependency.
Transport costs	The results of a study on the potential economic impacts of a global increase in transport costs due to a carbon price of $200/t CO_2. The study finds that high-income economies, such as the EU, Canada, Japan, and the USA, would see minor increases or small reductions in GDP and similar reductions in exports. However, the impact on investment varies across regions, with the EU experiencing the most significant negative impact, while Japan and the USA see increases in investment driven by import substitution. Middle-income developing countries and emerging economies would have small overall impacts, with China, India, Russia, Brazil, and the rest of South America having net positive economic impacts. However, some regional aggregations of economies, such as South Asia and Southeast Asia, experience net negative impacts. Small Island Developing States (SIDS) and Least Developed Countries (LDCs) have net negative impacts, with only five SIDS included in the study. The results for LDCs are particularly variable, with approximately twice as many having net negative impacts than those with net positive impacts. The quality of data available for many of these economies limits the depth of analysis, but SIDS and LDCs are less able to counterbalance the consequences on the sectors of their economy negatively impacted.
Food security	Transport of specific types of cargo like perishable goods may be negatively affected when higher transport costs change for example optimal speeds. Considering this specific impact is also important from the perspective of ensuring food security, especially with respect to possible changes in import prices of essential food commodities, additional time or possibility to procure them.

Table 5. cont. Summaries of initial impact assessments

ISWG-GHG 12/3/4 (Austria, et al.)	
Disaster response	Some States are also more prone to disasters than others and may be less resilient, e.g., because they are more likely to be hit by disasters that affect the entire State rather than a specific region within a State. Apart from changes in transport costs, which may impact disaster relief costs, a GFS could also require different inventory requirements for essential goods.
Cost-effectiveness	N/A
Socio-economic progress and development	Increase in the use of low- and zero-GHG fuels in the shipping industry is expected to have a marginally positive impact on employment for seafarers, as it will require additional investment in their training and certification. Equipment suppliers, ship construction and repair, and R&D employment are expected to see more positive impacts, while job growth in the bunkering sector may be more restrained. The use of non-drop-in fuels and innovative propulsion technologies will require the highest innovation efforts. The further development of internal combustion engines and energy efficiency measures, including the use of wind assistance, is also expected to increase. The uptake of zero-emission ships is expected to have a significantly positive impact on public health due to the decrease in air pollution.

ISWG-GHG 15/3/7 (China)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	Qualitative
Cargo value and type	N/A
Transport dependency	N/A
Transport costs	N/A
Food security	N/A
Disaster response	N/A
Cost-effectiveness	N/A
Socio-economic progress and development	N/A

MEPC 76/7/1 (Marshall Islands and Solomon Islands)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	An initial assessment finds that the long-term impact of the proposed GHG levy is most likely positive overall for the sector. Should negative impacts occur, most are likely short- to medium-term in nature, and in most instances are likely no more than minor and are routinely already absorbed from oil market and freight price variations currently. Disproportionate negative impacts are most likely found in the case of a small and narrow number of States. Such States are highly likely to already experience disproportionately high shipping costs combined with low security of transport supply.
Cargo value and type	N/A
Transport dependency	N/A
Transport costs	N/A
Food security	N/A
Disaster response	N/A
Cost-effectiveness	N/A
Socio-economic progress and development	N/A

ISWG-GHG 12/3/9 (Argentina et al.)	
Impact	**Assessment of Impacts**
Geographic remoteness of and connectivity to main markets	Qualitative
Cargo value and type	N/A
Transport dependency	N/A
Transport costs	N/A
Food security	N/A
Disaster response	N/A
Cost-effectiveness	N/A
Socio-economic progress and development	N/A

Table 6. Summary of approaches to the impact assessments relating to proposals of mid-term measures

Impact	ICS	Japan	Norway	EU	Argentina et al.	China	RMI & SI
Geographic remoteness of and connectivity to main markets	Variable impact depending on the quanta used and type/value of goods-ranging from insignificant impacts for quantum less than \$100/t CO_2 for iron ore, to very high impacts on foodstuff (21% for a levy of \$100 and up to 83% for a levy of \$400).	Not investigated	Not investigated	Higher transport costs affecting States away from main markets. States producing and exporting renewable fuels will be positively impacted. Risk of modal shift and product substitution for nearby trading partners.	qualitative	Qualitative	Long-term impact of proposed GHG levy is most likely positive overall. Disproportionate negative impacts are most likely in small and narrow number of States. Such States are.
Cargo value and type	All cargoes examined are volatile. Impact on the price of cargoes on delivery fell within the average monthly volatility of delivered cargo prices the during 2021, except for container trades.	Not investigated	Not investigated	Higher transport costs may affect trade of low-value cargoes more negatively than high-value cargoes, including foodstuff for which food security shall be ensured especially for essential food commodities.	Not investigated	Not investigated	Not investigated
Transport dependency	Qualitative	Not investigated	Not investigated	Qualitative	Not investigated	Not investigated	Not investigated
Transport costs	No significant impact beyond volatility of fuel oil prices and in freight rates due to supply chain and war crises.	Impact of contribution can be compared against normal volatility of freight including at times of crises such as COVID 19. rates, as had been	Modest (2%) increase in consumer prices for SIDS.	High-income economies would experience minor increases, small reductions in GDP Middle-income countries have small overall impacts. Some regional aggregations of economies, such as South Asia and Southeast Asia, experience net negative impacts; while SIDS and LDCSs have net negative impacts,	Not investigated	Not investigated	Not investigated
Food security	Impacts of the levy quanta examined generally fall within the average monthly volatility for applicable bulk carriers used to move key food stuffs in bulk. For containerized perishable cargoes, a levy initially set above \$100 /t CO_2 will large impacts on the price of delivered perishable foodstuffs.	Not investigated	Prices for imported foods will likely increase, with impact on food security.	Qualitative	Not investigated	Not investigated	Not investigated

UNCTAD conducted simulations based on their initial observation, which suggested that the proposals including mid-term measures by IMO (both technical and economic) fit broadly within the guidelines established by three simulations of increasing (maritime logistics) costs:

- Scenario 1: increase of 10%

• Scenario 2: increase of 30%

• Scenario 3: increase of 50%

Figure 32 demonstrates that, from a worldwide perspective, each of the three scenarios indicates alterations in trade movements amounting to just over 1% on average. The trade numbers in figure 32 are for total goods and services trade. Correspondingly, these changes result in a comparatively minor influence on actual GDP, amounting to less than 0.1%. It is worth noting that all three scenarios showcase negative changes. It is anticipated that a rise in the expenses related to maritime logistics will inevitably lead to a reduction in both trade and GDP.

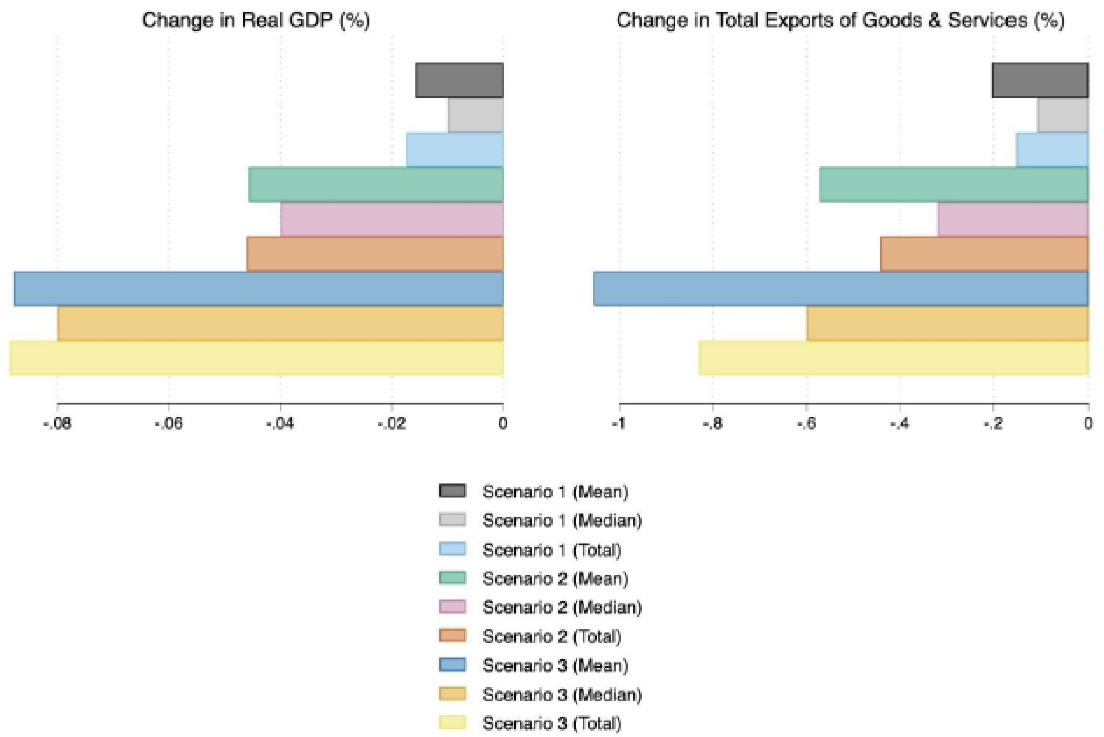


Figure 32. World average, median, and total macroeconomic impacts by situation, percentage change relative to 2015 baseline. Source: MEPC 80/INF.39/Add., 1

The remainder of this section is taken from the publication *Carbon Pricing in Shipping* (ITF, 2022). This report reviews the effectiveness of carbon pricing, how it might be applied to the shipping sector, and with what effects. It also evaluates recent proposals by countries to introduce a price on shipping's carbon emissions and examines related policy issues. The analysis draws on interviews and exchanges with stakeholders and experts who participated in the ITF's Common Interest Group on Decarbonising Shipping from June 2021 to

November 2022. Five of the submitted proposals relate to carbon pricing. These include proposals for global carbon levies (one put forth by the Marshall Islands and Solomon Islands and another by the International Chamber of Shipping and Intercargo), a global feebate system (from Japan), a global emission trading system for shipping (proposed by Norway), and a reward and funding system (by Argentina, Brazil, China, South Africa, the United Arab Emirates and Uruguay, hereinafter referred to as Argentina et al.). The proposals are outlined in table 7. In addition, all 27 EU Member States, Norway and the European Commission submitted a proposal for a global GHG fuel standard (document ISWG-GHG 12/3/3, hereinafter referred to as Austria et al.). This proposal is not a specific carbon pricing proposal but it is closely related.

Table 7. Proposals for carbon pricing or fuel standards submitted to the International Maritime Organization. Source: ITF, 2021-2022

Proposal	Submitted by	Year	IMO reference
Universal mandatory greenhouse gas emission levy	Marshall Islands, Solomon Islands	2021	MEPC 76/7/12
Levy-based market-based measures	International Chamber of Shipping, Intercargo	2021	ISWG-GHG 10/5/2 ISWG-GHG 12/3/7
Zero-Emission Vessels Incentive Scheme	Japan	2022	MEPC 78/7/5
International Maritime Sustainability Funding and Reward mechanism	Argentina, Brazil, China (People's Republic of), South Africa, United Arab Emirates	2022	ISWG-GHG 12/3/9
Emission Cap and Trade System	Norway	2022	ISWG-GHG 12/3/13

Note: The different documents referenced under "IMO reference" are available to delegates of IMO meetings (IMODOCs) on a password-protected part of IMO's website. They are referenced in the Reference section of this report, though they are not publicly available. This report refers to the documents with the names used in IMO meetings, for example: "Argentina et al." refers to the proposal by Argentina, Brazil, People's Republic of China, South African and United Arab Emirates. MEPC refers to IMO's Marine Environment Protection Committee; ISWG-GHG to IMO's Intersessional Working Group on Reduction of GHG emissions from Ships. The IMO reference is the numbering used in the IMO meetings to identify the documents.

Source: Marshall Islands and Solomon Islands (2021), ICS and Intercargo (2021), Japan (2022a), Argentina et al. (2022), Norway (2022).

The proposal from the Marshall Islands and Solomon Islands suggests that a carbon price is set at an amount that would create a level playing field between heavy fuel oil and zero or near-zero GHG emission fuels. The proposal suggests that a carbon price of $250-300 per tonne of CO_2e by 2030 (table 8) achieves this goal.

The proposal by ICS and Intercargo is similar in its basic premise of a global fuel levy. However, it does not indicate the carbon price it wants to set. Its objective is to bridge the price gap, but it also states that "it will be premature to impose a disproportionally high carbon price on shipping".

Japan's proposal is an explicit feebate system. It uses revenues from a carbon levy as rebates for zero or near-zero GHG emission fuels. In this proposal, the carbon price corresponds to the funds needed to provide enough rebates to zero or near-zero GHG emission fuels to make the transition to them commercially viable.

Table 8. Design mechanisms of proposals submitted to the International Maritime Organization. Source: ITF, 2021-22

Proposal	Carbon price	Which ships benefit?	Which ships pay?
GHG levy (Marshall Islands, Solomon Islands)	USD 100 per tonne CO_2e (2025) USD 250-300 per tonne by 2030	Dependent on re-investment of revenues from levy	All ships, according to their CO_2e emissions
Levy (International Chamber of Shipping, Intercargo)	Not defined	Dependent on reinvestment of revenues from levy	Ships according to carbon intensity of their fuels
Feebate (Japan)	USD 56-73 per tonne CO_2 (2025) USD 135-176 per tonne by 2030	Zero emission ships	All the other ships
Reward and penalty system (Argentina et al.)	n.a.	Ships with emissions below reward benchmark	Ships with emissions above contribution benchmark
Cap and trade (Norway)	Market price of cap and trade	Ships with low GHG emissions	Ships with high emissions
Global fuel standard (Austria et al.)	Cost compliance with standard		

Note: Argentina et al. refers to Argentina, Brazil, People's Republic of China, South Africa and United Arab Emirates. Austria et al. refers to all EU27 countries, Norway and the European Commission.

Source: Marshall Islands and Solomon Islands (2021), ICS and Intercargo (2021), Japan (2022a), Argentina et al. (2022), Norway (2022), Austria et al. (2022a).

Argentina et al. (2022) proposed an "International Maritime Sustainability Funding and Reward" mechanism and bears resemblance to the Japanese proposal in that the taxes collected from high CO_2 emission-emitting ships are paid to ships that emit less CO_2. The specificity of this proposal, though, is that it uses the IMO Carbon Intensity Indicator (CII) mechanism to define the upper and lower benchmarks.

Norway proposed an ECTS. Central to the proposal is a cap on emissions that will ensure an annual reduction of total GHG emissions along an agreed pathway aligned with the ambitions of the 2018 Initial IMO Strategy and the 2023 IMO GHG Strategy, which was at the time of submission still to be agreed upon and slated for adoption in 2023. The proposal from Norway conceives the ECTS as a closed system specific to the shipping sector, referred to in table 7.

Austria et al. proposed a global fuel standard requiring all ships to use fuels or energy sources with a GHG intensity below a specific limit value. GHG intensity is here defined as GHG emissions per unit of energy used on board a ship. The proposal anticipates a transitional period during which not all ships may be capable of sailing on zero or near-zero GHG emission fuels and proposes "flexibility mechanisms" to deal with this situation.

The proposals by ICS and Intercargo, Japan and Argentina et al. cover only CO_2 emissions. Those from the Marshall Islands and Solomon Islands, Norway and Austria et al. cover all GHG emissions (table 9). Of the six proposals, the proposal by the Marshall Islands and Solomon Islands and Austria et al. explicitly cover WTW emissions. Norway's proposal would cover TtW emissions but is open to expanding to WTW emissions if solid methods of measuring WTW emissions were available. In refinements to its proposal, Japan indicates that zero-emission fuels that have higher WTW GHG emission factors than fossil fuels can be excluded from the scope of the reward. In the proposal by Argentina et al., WTW emissions are, to a certain extent, considered as benchmark levels and would be adjusted for ships that have consumed "a certain proportion of alternative low/zero-carbon fuels (to be defined in LCA guidelines)". Table 8 shows that two proposals do not define which ships will be covered by the scheme, two proposals cover all ships larger than 5,000 GT, one proposal covers all ships larger than 400 GT and one proposal leaves this boundary open.

Table 9. Types of emissions covered in the proposals to the International Maritime Organization. Source: ITF, 2021-22

Proposal	Ship size	Carbon emissions (CO_2) or all greenhouse gas (GHG) emissions?	Well-to-wake emissions or tank-to-wake emissions?
GHG Levy (Marshall Islands, Solomon Islands)	Not defined	GHG	Well-to-wake
Levy (International Chamber of Shipping, Intercargo)	Ships > 5 000 GT	CO_2	Tank-to-wake, open to expanding to well-to-wake
Feebate (Japan)	Ships > 5 000 GT	CO_2	Tank-to-wake, but exclusion from scope if WTW of zero-emission fuels are higher than WTW from fossil fuels.
Reward and penalty system (Argentina et al.)	Not defined	CO_2	Tank-to-wake
Cap and trade (Norway)	Ships > 400 GT	GHG	Tank-to-wake, open to expanding to well-to-wake
Global fuel standard (Austria et al.)	Ships > 5 000 GT or 400 GT	GHG	Well-to-wake

Note:GT= gross tonnage. Argentina et al. refers to Argentina, Brazil, People's Republic of China, South Africa and United Arab Emirates. Austria et al. refers to all EU27 countries, Norway and the European Commission.

Source: Marshall Islands and Solomon Islands (2021), International Chamber of Shipping and Intercargo (2021), Japan (2022a and 2022b), Argentina et al. (2022), Norway (2022), Austria et al. (2022a).

Table 10 summarises how the revenues generated might be used. Two of the six proposals provide indicative numbers on revenues from their carbon pricing proposals. ICS and Intercargo mention that a levy of $50 per tonne of CO_2 emitted would generate almost $40 billion per year. The Norway proposal would generate $130 billion to $140 billion annually from 2030. Extrapolating the ICS and Intercargo numbers to the Marshall Islands and Solomon Islands' proposal suggests revenues in that scheme of $80 billion per year by 2025. The freely-available revenues in the proposals of Japan and Argentina et al. will likely be smaller, if only because, by design, they will use a large share of the contributions to reward lower-emission ships. The Argentina et al. proposal put this share at 40%, while Japan leaves it undefined. In principle, Austria et al.'s proposal would not generate any revenues. However, it mentions the possibility of "flexibility mechanisms", one of which would be contributions of under-complying ships to an IMO GHG fund.

Table 10. Revenue use in carbon pricing proposals submitted to the International Maritime Organization. Source: ITF, 2021-22

Proposal	Main spending categories	Administered by
GHG Levy (Marshall Islands, Solomon Islands)	Climate change adaptation/mitigation (at least 51%) Research development and deployment (up to 33%) Administrative costs (16%)	Green Climate Fund[1] International Maritime Research and Development Board (to be established)
Levy (International Chamber of Shipping, Intercargo)	Research and development, new bunkering infrastructure, assist maritime GHG reduction of developing countries	IMO Climate Fund (to be established)
Feebate (Japan)	Incentives for first movers, technical co-operation, carbon offset credits	IMO's Integrated Technical Cooperation Programme[2]
Reward and penalty system (Argentina et al.)	Rewards to ships with emissions below benchmark (40%) Capacity building (30%) Research development and deployment (20%) Administration costs (10%)	An International Maritime Sustainability Funding and Reward Board (to be established) within the IMO structure
Cap and trade (Norway)	Address disproportionate impacts on states, uptake low- and zero-emission fuels, production of zero-emission fuels, infrastructure, R&D	Green Climate Fund

Notes: 1. https://www.greenclimate.fund/; 2. https://www.imo.org/en/OurWork/TechnicalCooperation/Pages/ITCP.aspx; IMO= International Maritime Organization; Argentina et al. refers to Argentina, Brazil, People's Republic of China, South Africa and United Arab Emirates.

Source: Marshall Islands and Solomon Islands (2021), International Chamber of Shipping and Intercargo (2021), Japan (2022a), Argentina et al. (2022), Norway (2022), Austria et al. (2022a).

Japan proposes that the main spending category (in addition to the rebates for zero-emission vessels that form the essence of the proposal) is technical co-operation to facilitate an equitable transition. The proposal singles out IMO's Integrated Technical Cooperation Programme, which could be enhanced to assist maritime GHG reduction efforts in vulnerable States. They suggest that this could help mobilise more significant amounts of external resources for projects, such as establishing new bunker fuel infrastructures.

Capacity-building also is a major spending category in the Argentina et al. proposal. This could be allocated to an International Maritime Sustainability Funding and Reward Board under the Organization's purview. Other major spending categories in this proposal are RD&D and administration costs. Similar spending categories feature in the Marshall Islands and Solomon Islands' proposal. There, the funds for RD&D could be allocated by a structure similar to the International Maritime Research Board suggested by shipping associations and discussed in various of the Organization's climate negotiations. The Marshall Islands and Solomon Islands' proposal foresees channelling spending for climate change adaptation and mitigation through the GCF of the UNFCCC. Norway's proposal suggests the same: the GCF would collect and allocate the revenues to mitigate disproportionate impacts on States and stimulate the uptake of zero or near-zero GHG emission fuels, the production of zero-emission fuels, infrastructure maintenance and R&D.

The UNCTAD (2023) evaluation, contained in document MEPC 80/INF.39/Add.1, focuses on candidate mid-term GHG reduction measures, providing an overview of various proposals, such as:

- International Maritime Sustainability Funding and Reward (IMSF&R)
- Zero-Emission Shipping Incentive Scheme (ZESIS)
- Emission Cap-and-Trade System (ECTS)
- Greenhouse Gas Fuel Standard (GFS)
- International Maritime Sustainable Fuels and Fund (IMSF&F)
- GHG Levy

These proposals are strategically designed to reduce the cost disparity between zero or near-zero GHG emission and conventional fuels, promote the adoption of cleaner fuels and extend support to developing countries. The impact assessments meticulously contemplate the repercussions for various States, paying particular attention to the necessities of developing countries, SIDS, and LDCs.

These assessments shed light on potential obstacles and advantages, which are expected to vary across different countries, with small States, LDCs, and SIDS potentially experiencing significant impacts. The Greenhouse Gas Fuel Standard (GFS) and Flexibility Compliance Mechanism (FCM) are notable among the proposals which collectively aim to mitigate concerns regarding market control and uphold environmental integrity. A proposed synergy of GFS with a levy system seeks to minimize the cost differential between zero and near-zero GHG emission fuels compared to traditional fuels, with the generated revenue supporting a fair and equitable transition.

Other proposals, such as the International Maritime Sustainability Funding and Reward Mechanisms aspire to amalgamate the objectives of other measures, encompassing ambition assurance, fund generation, and the progression of research, development and deployment (RD&D).

The document MEPC 80/INF.39/Add. 1 provides an exhaustive recapitulation of the proposals, delving into their potential impacts.

Key points, as mentioned above, include the main results in terms of:

- **Geographic remoteness:** Diverse impacts contingent on the levy quantum and maritime dependence.
- **Cargo value and type:** Disparate effects on different goods, with low-value cargoes potentially more adversely impacted.
- **Transport dependency:** Countries heavily reliant on maritime transport may encounter substantial hurdles.
- **Transport costs:** Predicted increased transport costs, necessitating focused attention on specific goods and vulnerable areas.
- **Food security:** Potential threats to food security due to price escalations, especially concerning essential commodities.
- **Socio-economic progress:** The proposals could contribute positively to decarbonization and public health, with a slight uptick in employment opportunities.

Moreover, other key points can be summarized as follows:

- **Carbon pricing policies**: 68 carbon pricing instruments worldwide, covering approximately 23% of global GHG emissions. Discussion includes both carbon taxes and emission trading systems (ETSs).
- **Environmental effectiveness**: carbon pricing mechanism generates technological changes, encouraging the adoption of cleaner marine fuels.
- **Country-specific insights**: Discussion includes the political acceptability of carbon pricing mechanism and global versus regional implementation.
- **Impacts on States**: Economic impact, sensitivity to carbon prices, and simulation results are presented.

Moreover, based on document MEPC 80/INF.39, an overview of the potential impact of different measures on States is provided below.

1. Universal mandatory Greenhouse Gas Levy (GHGL)

The GHGL is a proposed financial measure to reduce GHG emissions by implementing a levy based on the principles of 'Polluter Pays' and 'Equity.' This initiative is designed to motivate a shift towards decarbonization. The levy's impact on countries will vary, influenced by factors such as geographical isolation, the value of transported goods, reliance on transport and the security of food supplies. It is anticipated that the GHGL will benefit disaster response capabilities and the cost-effectiveness of such operations. The primary advantage of the GHGL is its potential to diminish the damages caused by climate change. However, it may also lead to an increase in transportation costs which would affect States differently. The exact impact on global trade is uncertain but it is expected to be minimal if decisive action is taken. The assessment is based on a qualitative analysis drawn from existing literature and studies, acknowledging that some impacts may elude quantification.

2. International Maritime Sustainability Funding and Reward (IMSF&R)

Early assessments of the IMSF&R's impact suggest that careful adjustment of its parameters could yield positive outcomes. A qualitative evaluation has identified possible adverse effects on transport supply, freight costs and international trade, with developing countries potentially being the hardest hit. Proposed mitigation strategies involve the allocation of carbon emission allowances for fuels used in developing countries, alongside funding for building capacity and transferring technology.

3. IMSF&F mechanism

The goal of the IMSF&F mechanism is to address greenhouse gases such as CO_2, CH_4 and N_2O. A thorough impact assessment is scheduled for Phase III of the Work Plan. The likelihood of various outcomes is still under evaluation, but there are already recommendations for mitigating negative impacts, including carbon emission allowances and funds dedicated to capacity-building. The initial findings suggest that the mechanism will positively contribute to GHG reduction efforts, with an estimated cost impact of less than \$12.5 per tonne of CO_2, unlikely to result in disproportionately adverse effects.

4. Feebate mechanism (ZESIS)

The ZESIS mechanism has undergone a comprehensive impact assessment, mainly focusing on maritime transport costs, using a simulation model of the global logistics intermodal network. While significant impacts are not expected in the early stages of the transition, the revenue generated will support projects in developing countries.

5. Revised IMSF&R

The proposal aims to achieve net-zero emissions by 2050, with a 2030 target for zero or near-zero GHG emission fuel production and adoption. It suggests a fixed contribution per tonne of CO_2 to the IMO Maritime Sustainability Fund (IMSF), minimizing the administrative burden on ships. The initial impact assessment indicates a 5% reduction in emissions by 2030, with funds supporting developing countries in the transition.

Positive impacts include encouraging low and zero GHG fuel production while negatives involve potentially increasing marine fuel costs. The proposal establishes the IMSF at no direct cost to States, benefiting all Member States in contributing to global decarbonization goals. Using data from Clarksons Research (2023), methodological tools show that a suggested contribution of $12.5 per tonne of CO_2 could achieve objectives without disproportionately negative impacts. The proposal emphasizes GHG reduction through economic incentives, with minimal administrative impact on ships and potentially significant benefits, particularly for developing countries.

6. Emission Cap-and-Trade System (ECTS) proposed by Norway

The ECTS, as proposed by Norway, discusses the potential impacts of the ECTS on the maritime industry. If implemented on the 2019 fleet, it would affect around 63,500 ships emitting 762 million tonnes of CO_2 annually. The ECTS is expected to significantly reduce GHG emissions and air pollution from fossil fuel use.

Projected carbon prices under the ECTS indicate a gradual increase, reaching \$200-\$210/tonne CO_2 by 2030 and \$300/tonne CO_2 in a "decarbonization by 2050" scenario. Positive outcomes include climate change mitigation, reduced air pollution and minimized negative impacts from fuel spills. However, potential negatives involve increased transport costs, reduced shipping activities and higher shipping service prices.

While cost distribution uncertainties exist, overall impacts on end users are expected to be relatively modest. The ECTS has revenue-generating potential from ship emission unit sales, offering a means to offset disproportionately negative impacts.

Smaller States, particularly SIDS heavily reliant on shipping, may face more significant impacts. To mitigate concerns, funds generated through the ECTS can be directed to the GCF to support investments in developing States and contribute to emissions reduction efforts.

7. Combination of GHG Fuel Standard (GFS) with a levy

Combining a GHG Fuel Standard with an additional levy is expected to lead to increased fuel costs. The probability of these costs having disproportionately negative impacts is considered low and it is suggested that adverse effects could be mitigated by reinvesting the revenue from the levy appropriately.

8. Greenhouse Gas Fuel Standard (GFS)

The GFS outlines both positive and negative impacts. Revenue distribution is a significant factor in mitigating potential negative consequences, particularly for SIDS and LDCs.

9. Simplified Global GHG Fuel Standard

The proposed measure aims to achieve a 5% reduction in GHG emissions from international shipping by 2030. It offers benefits to all Member States, including LDCs and SIDS. However, it introduces additional costs for compliant marine fuel. The administrative burden on Member States is expected to be limited compared to other measures. Clarksons Research used comprehensive data to assess the impact of fuel cost increases. Disproportionately adverse effects are unlikely, even with fuel cost increases exceeding $150 per tonne. Mitigation efforts may be unnecessary if the additional cost of zero or near-zero GHG emission fuels falls within $40 to $80 per tonne. The measure seeks to balance climate change mitigation, sustainability and the concerns of Member States.

Answer to research questions:

Question: What are the impacts of candidate mid-term measures on various determinants of maritime transport costs, and consequently, on the costs of imported products?

The impact of candidate mid-term measures on various determinants of maritime transport costs, as outlined in Rojon et al. (2021), including additional elements found in the literature review on subtask 4, and their effects on the costs of imported products, as outlined in the UNCTAD (2023) latest *Review of Maritime Transport*, present a multifaceted scenario:

Price Elasticities and Carbon Tax Influence:

- Across industries and products, it has been identified that fuel cost increases, which are used as indicators for maritime carbon pricing, have notable yet varying adverse impacts on the distance-weighted weight of traded goods and on CO_2 emissions from maritime transport. These effects pertain to global trade, with bunker price elasticity ranging from -0.03 to -0.52 (Rojon et al., 2021), showcasing varying responses to changes in shipping costs.

- Lowering carbon emissions in international trade is most significant for products with low value-to-weight ratios (e.g. fossil fuels, ores, cereals) under a relatively low-level carbon tax ($40/tonne) (Rojon et al., 2021). Conversely, goods with higher value-to-weight ratios (like furniture and motor vehicles) exhibit notably lower emissions reduction.

Shifts in international trade and GDP impact:

- Implementing carbon pricing tends to reduce trade in low-value, high-volume goods from distant sources while favouring high-value, low-volume commodities. However, the effect on real GDP, assuming a per tonne of CO_2 charge, remains below 0.5% (Rojon et al., 2021).

Cost pass-through rates and economic implications:

- The rate at which levy costs transfer to consumers fluctuates (UNCTAD, 2023), suggesting potential long-term effects of a carbon tax on pass-through rates, likely higher than those from short-term oil price fluctuations.
- A substantial global maritime carbon tax ($90 per metric tonne of CO_2) does not significantly impact global economies (UNCTAD, 2023).

Regional impact and carbon tax scenarios:

- Higher carbon prices ($100 to $300 per tonne of CO_2) could significantly impact specific countries, leading to substantial cost increases in freight rates and trading prices for bulk cargoes (e.g. iron ore, coal) (UNCTAD, 2023).
- A gradual carbon tax increase to $75 per tonne in 2030 and $150 per tonne in 2040 would decrease maritime CO_2 emissions below business-as-usual levels, generating substantial revenues. However, this increment would slightly increase shipping costs (0.075% of global GDP in 2030) (UNCTAD, 2023).

Challenges and recommendations:

- Comprehensive impact assessments pose challenges such as ship status during ballast, emissions allocation, and managing revenue from measures (UNCTAD, 2023).

Leveraging empirical evidence from other sectors under carbon pricing could aid in assessing these impacts.

- The distribution of costs and benefits among stakeholders involved in implementing these measures and the need for expertise in fund management, economic regulation and capacity-building are highlighted (UNCTAD, 2023).

The literature review underlines the intricate nature of assessing mid-term measures' impacts on maritime economics. It points out the varied responses to carbon pricing across industries. It underscores the challenges in comprehensively evaluating their effects, stressing the importance of leveraging empirical evidence from other sectors and addressing stakeholder concerns for effective implementation.

<u>Question: Are there substantial gaps in the existing literature concerning this subject matter?</u>

The existing body of literature, although comprehensive in exploring various facets of GHG mitigation measures in maritime transport, does exhibit significant gaps:

Historical and empirical deficiency:

- One primary gap arises from the need for robust historical or empirical evidence within the shipping domain. In many research studies, indicators such as bunker prices are frequently used as substitutes to gauge price elasticity (UNCTAD, 2023). Nonetheless, this approach might encompass the varied elasticities observed across different countries, commodities, types of vessels and travel distances.

Varied impact evaluation:

- While the literature covers a range of potential impacts on maritime transport costs under GHG mitigation measures, there is a gap in the depth of evaluation concerning certain critical aspects (Austria et al., 2022; UNCTAD, 2023). For instance, the comprehensive assessment may thoroughly investigate the detailed ramifications of diverse GHG mitigation measures on specific economic sectors or geographical areas.

Challenges in comprehensive assessment:

- The complexity of a comprehensive impact assessment presents several challenges. Understanding the status of ships during ballast, emissions allocation to different regions and evaluating the costs and benefits from revenue use and distribution remain areas that require more comprehensive study (UNCTAD, 2023).

Limited focus on demand changes:

- The literature acknowledges a limitation in understanding changes in shipping demand due to the need for precedents or schemes within the shipping domain. Observing changes in fuel prices is suggested as an indicator of shipping price elasticity, yet there needs to be more empirical evidence (UNCTAD, 2023).

Stakeholder engagement and expertise development:

- Engaging diverse stakeholders and developing expertise for implementing, reviewing and monitoring technical measures pose a challenge. Further exploration and development of this expertise are to be taken into consideration for effective policy design and execution.

Data sufficiency and reliability:

- Addressing the needs of SIDS and LDCs necessitates enhanced data availability and reliability. Leveraging databases such as the ones at UNCTAD and the World Bank can aid in supporting these requirements (UNCTAD, 2023).

Summarizing, while the literature review provides a comprehensive overview of GHG mitigation measures in maritime transport, there may be scope for analysing further historical evidence, more nuanced impact assessments, understanding demand changes, stakeholder engagement and data reliability. These gaps present avenues for further research and exploration to bolster the depth and precision of policy implementations and their subsequent evaluations.

3.2.3 Greenhouse gas mitigation measures in shipping and zero or near-zero GHG emission fuel viability

Various reports have revealed significant insights in reviewing existing literature pertinent to the potential impact of implementing GHG mitigation measures on shipping costs and its broader influence on the eight impact criteria outlined in the 2023 IMO GHG Strategy.

The 2023 EMSA report, investigating biofuels for shipping, highlights critical aspects concerning carbon cost as a core component of OPEX within maritime operations. Commencing in 2024, the maritime shipping sector will integrate into the European Emissions Trading System (EU ETS), marking a pivotal regulatory milestone. This integration mandates shipping companies to surrender allowances for CO_2 emissions, aligned with the specified geographic boundaries of the EU ETS framework.

The incurrence of carbon costs hinges on fossil fuel combustion aboard ships operating within the scope of the EU ETS. Projected EU ETS prices, estimated at €46 per tonne by 2030 and escalating to €150 per tonne by 2050, drive the computation of these costs.

These costs are imposed per tonne of CO_2 emitted, albeit with varying rates contingent upon voyage nature, notably distinguishing between those voyaging between the EEA and non-EEA ports. The distinction between EEA and non-EEA voyages affects carbon emissions. Regulation 2175/2005 applies only to EEA voyages, requiring ships over 400 GT to monitor and report emissions. This adds to EEA voyage costs and may increase time spent in EEA States.

Biofuels stand as a unique exception within this framework, assumed to bear zero carbon costs due to their accounted zero CO_2 emissions. This distinction positions biofuels as an intriguing avenue within carbon cost considerations, presenting a promising prospect for sustainable and environmentally conscious shipping practices.

Regarding biofuels:

- They offer a viable avenue for shipping decarbonization owing to their compatibility with existing infrastructure and seamless integration (drop-in nature).
- Adopting biofuels minimizes retrofitting needs and poses negligible risk-related implications.
- However, their adoption faces hurdles due to high fuel costs, prompting consideration for potential benefits from a levy or emission trading mechanism to alleviate expenses.
- Anticipated as a significant driver for biofuel adoption, the Fit-for-55 package holds promise for the industry's future.

- The absence of universally-accepted sustainability criteria underscores the necessity for harmonized standards, enabling broader biofuel integration.
- Establishing explicit control, verification and certification mechanisms is imperative for consistency and deterring fraudulent activities linked to biofuel sustainability.

Moving forward, the 2023 EMSA report *Potential of Ammonia Fuel in Shipping* and risk-based case studies, focuses on carbon costs as operational expenditure, particularly in contrast to VLSFO. Notably, blue and green ammonia bear no carbon costs, unlike VLSFO.

Additionally, the examination of hydrogen as a shipping fuel in the 2023 EMSA report *Potential of Hydrogen as Fuel for Shipping*, provides stakeholders and regulators with detailed information on hydrogen as a marine fuel, covering its properties, production, suitability and sustainability. It also includes analyses of regulatory frameworks, techno-economic assessments and risk-based case studies, offering insights into the commercial and safety aspects of using hydrogen in marine applications. Several notable observations emerge:

- Green hydrogen production remains nascent, heavily contingent on the growth of renewable electricity production.
- To address the need for cost-effective green hydrogen, operational efficiency of electrolysers and adequate storage facilities are suggested.
- While hydrogen is considered a future fuel for short-sea shipping, technological limitations exist for deep-sea shipping, necessitating diverse storage solutions.
- Techno-economic considerations indicate that hydrogen-powered vessels' total ownership cost may approach parity with fossil-fuelled vessels by 2050 under specific conditions, highlighting the significance of decreasing hydrogen production costs and increasing vessel carbon pricing.
- Furthermore, the report emphasizes the presence of zero or near-zero GHG emission fuels with a lower additional total cost of ownership (TCO), supporting the transition to zero-carbon shipping.

Addressing these insights suggests the need for international or regional policies to bridge the gap between blue or green hydrogen and conventional fuels. Simultaneously, market incentives for low or zero-carbon freight facilitate this transition.

3.2.4 Carbon pricing

Carbon pricing can take the form of carbon taxes or ETS, among other mechanisms. As of 2022, 30 carbon taxes and nine ETSs have been implemented at the national level worldwide while the European Union (EU) ETS prices emissions in EU and European Free Trade Association countries (Parry et al., 2022). Many subnational pricing schemes are also operating, the largest being California's ETS. GHG emissions subject to national and subnational carbon pricing, however, vary from below 30% in some cases to more than 70% in others. Economy-wide average prices vary from below \$5 to over \$100 per tonne (see figure 33 and figure 34).

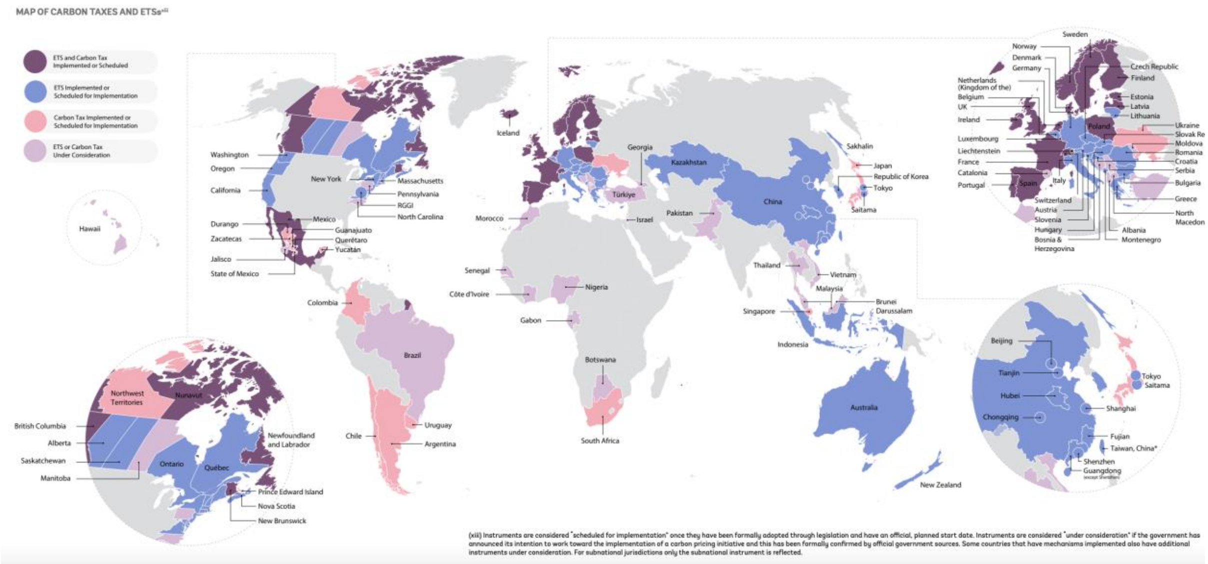
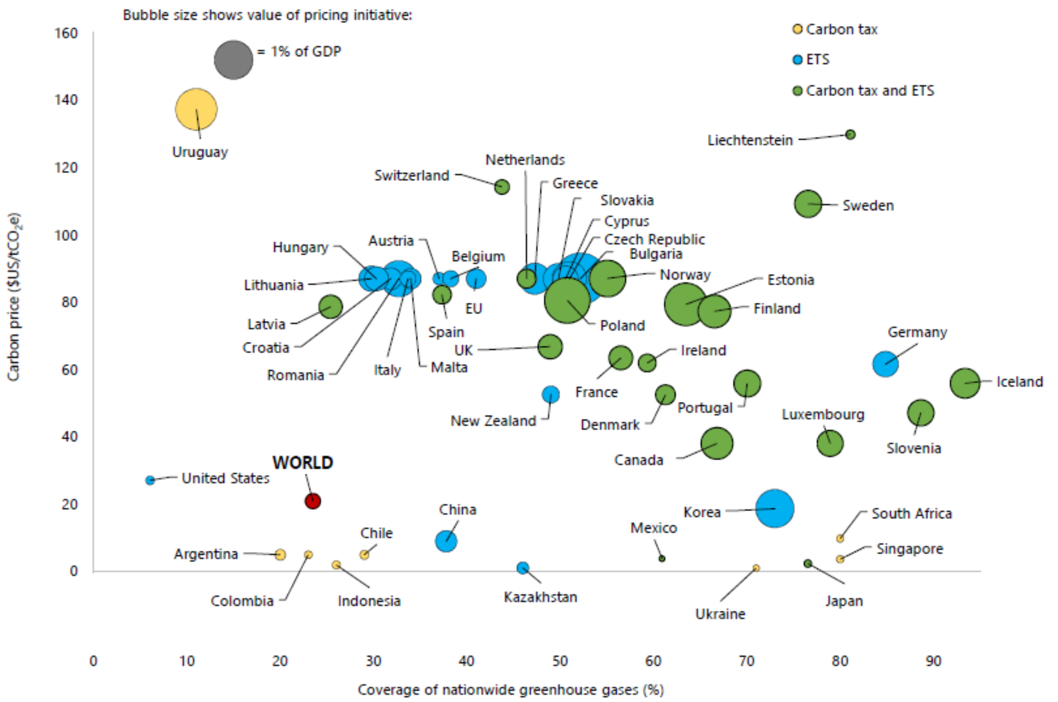


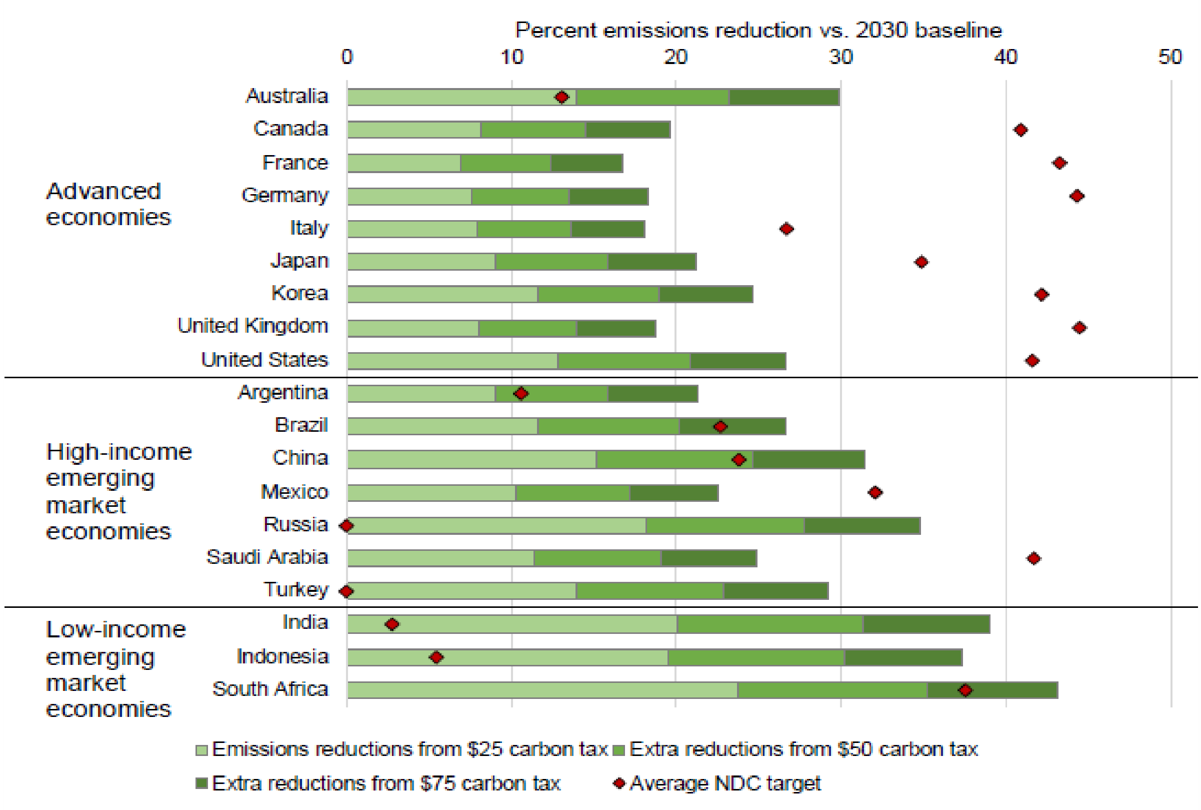
Figure 33. Summary map of regional, national and subnational carbon pricing initiatives. Source: World Bank group, 2023



Sources: Government websites; WBG (2022); and IMF staff calculations.
Notes: EU ETS includes Iceland, Liechtenstein, and Norway. Prices are emissions-weighted averages between schemes at national, subnational and, if applicable, EU level. At present, China's system takes the form of a tradable emissions intensity standard with no fixed cap on emissions. Mexico does not include subnational schemes due to lack of coverage data.

Figure 34. Subnational, National and Regional Carbon Pricing Schemes by Country. Source: Parry et al., 2022

As regards the benefits of carbon taxes, a $50 carbon price would potentially cut CO_2 emissions in G20 countries by around 15-35% below BAU levels in 2030 (Parry et al., 2022). However, this is below the commitments that many countries have made in their NDCs, submitted for the 2015 Paris Agreement (figure 35) (Parry et al., 2022).



Source: IMF staff using the Climate Policy Assessment Tool.
Note: Pledges assume CO_2 emissions are reduced in the same proportion to pledged reductions in greenhouse gases. BAU = business as usual; NDC = nationally determined contribution.

Figure 35. CO_2 Reductions below BAU for Mitigation Pledges and Carbon Pricing, G20 Countries 2030. Source: IMF, 2022

The IMF (2022) reported that a carbon price of $50 per tonne could potentially raise revenues by approximately 0.5-2% of GDP in 2030 (Figure 36).

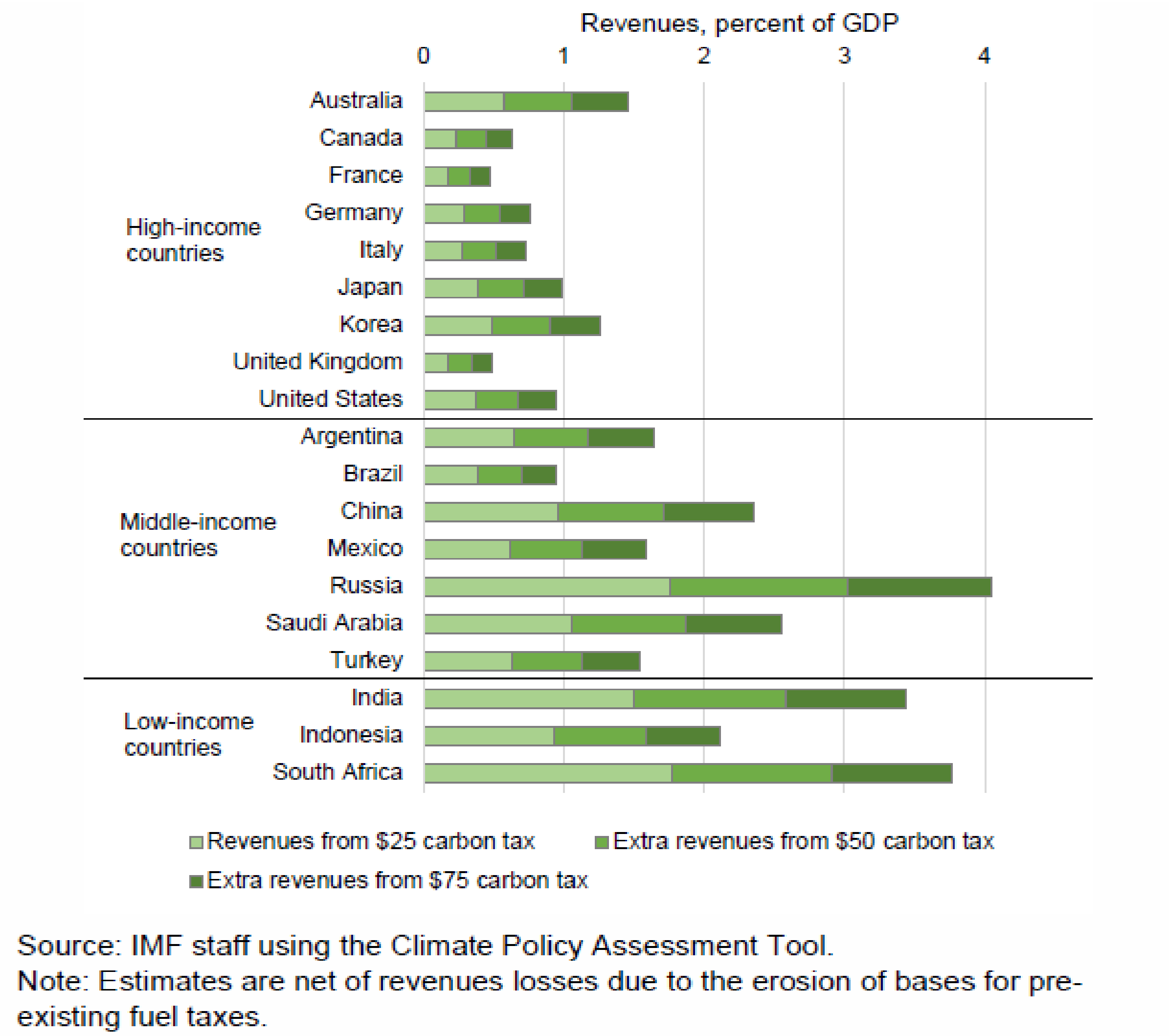
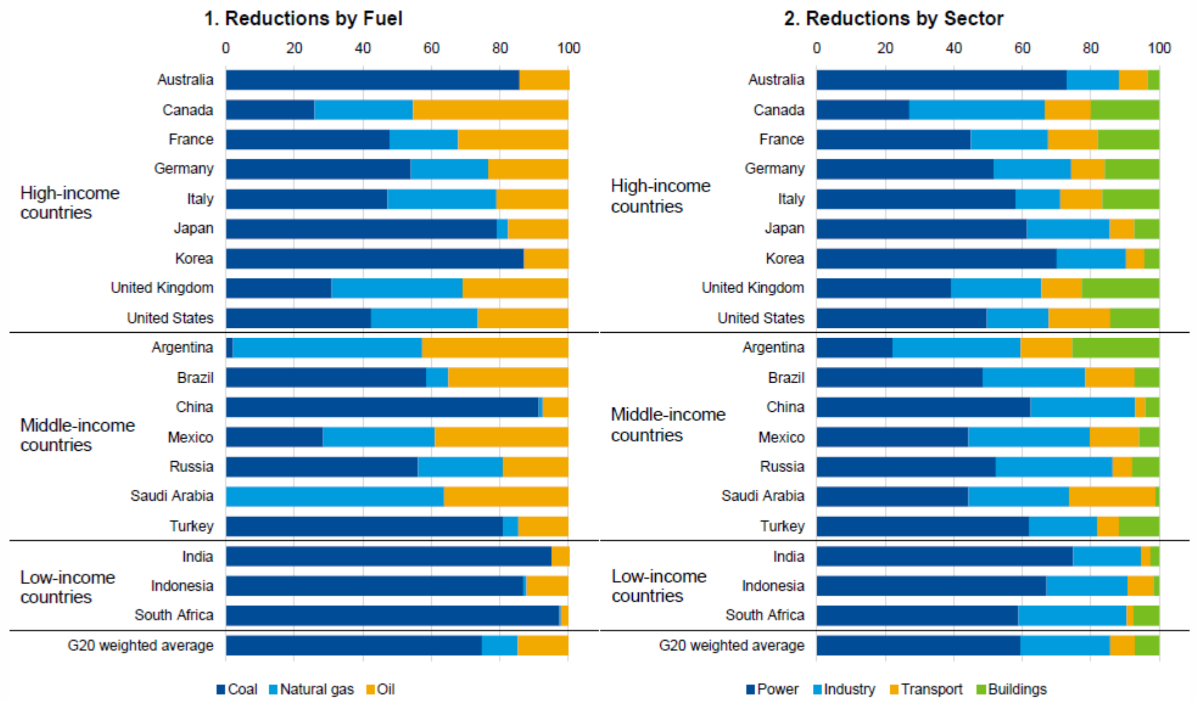


Figure 36. Fiscal Benefits from Carbon Pricing, 2030. Source: IMF, 2022

According to the IMF (2022), the welfare costs in G20 countries resulting from a carbon price of $50 in 2030 could range between 0.1% and 0.6% of GDP (figure 37). However, this estimate is contingent upon factors such as the specific carbon price, the emissions intensity of GDP under business-as-usual conditions and the proportional decrease in emissions achieved through pricing.



Source: IMF staff using the Climate Policy Assessment Tool.
Note: Estimates are for a $75/50/25 carbon price for high/medium/low-income countries. Panel 1 is for direct emissions (not emissions embodied in electricity use). Buildings corresponds to the definition countries use in reporting their emissions to the United Nations Framework on Climate Change and includes fossil fuel CO_2 emissions from residences, services, agriculture, and forestry; emissions from industrial buildings are included under industry.

Figure 37. Breakdown of CO_2 Reductions by Fuel/Sector under Carbon Pricing, 2030. Source: Parry et al., 2022.

With respect to the allocation of revenues, IMF (2022) comments that some revenues can be used for targeted assistance benefiting low-income economies by spreading the benefits more equitably across populations (table 11).

Table 11. Options for Use of Carbon Tax Revenues. Source: Parry et al., 2022

Instrument		Metric			
		Impact on Economic Efficiency	Impacts on Income Distribution	Administrative Burden	Political Feasibility
General Revenue Uses	Public investment	Potentially significant (high fiscal multipliers, especially for low-carbon investments)	Can disproportionately benefit low-income households (for example, if provides basic education, health, infrastructure), but depends on implementation	Modest; requires strong public investment management	Can be popular, with green investment especially favored in climate-concerned countries
	Tax reductions	Can improve incentives for work effort and investment and reduce incentives for the black economy and tax evasion	Can be designed to be progressive (for example, via increases in personal income tax thresholds)	Minimal	Popular with beneficiaries (for example, households for personal cuts, firms for corproate income tax cuts)
	Deficit reduction	Lowers future tax burdens and macro-financial risk	Depends on country circumstances	Minimal	Does not garner politcal support
Assistance to Households	Universal lump-sum transfers	Forgoes efficiency benefits (for example, no enhanced incentive for work effort)	Progressive (disproportionately benefits the poor)	New capacity may be needed (but should be manageable)	Mixed, with some households/firms favouring or disliking lump-sum transfers
	Means-tested cash transfers or social assistance	Forgoes efficiency benefits, but typically requires only a small share of revenues	Effective at helping low-income groups if transfers are well targeted or if social safety nets are comprehensive	Low if builds on existing capacity, otherwise significant	Generally popular
	Direct assistance for household energy bills	Forgoes efficiency benefits; reduction in environmental effectiveness depending on design	Provides partial relief for households (but does not help with indirect pricing burden)	Low if builds on existing capacity, otherwise significant	Generally popular

The IMF reports that there is wide divergence in pre-existing carbon charges across not only countries but also fuels/sectors within countries, see table 12. Moreover, Parry et al. (2022) found that the inclusion of negative figures in their analysis on carbon pricing in G20 countries by fuel and sector in 2020 can be attributed to the existence of subsidies, the execution of carbon pricing strategies and the varied taxation frameworks employed by individual countries in order to fulfil environmental and economic goals.

Table 12. Excise Taxes by Fuel and Sector in 2020, G20 Countries, (Expressed in charges per tonne CO2). Source: Black et al., 2021

	power			industry			transportation[b]		buildings[c]	
	coal	natural gas	oil	coal	natural gas	oil	gasoline	diesel	natural gas	oil
Argentina	0	- 31	19	5	0	33	105	45	- 41	1
Australia	0	0	79	6	24	96	157	99	- 54	68
Brazil	5	106	20	42	106	23	149	42	203	65
Canada	5	- 34	14	5	- 45	90	157	83	- 9	97
China	3	70	6	4	70	35	168	65	- 24	49
France	- 7	113	79	29	111	192	377	262	93	208
Germany	14	- 22	31	- 3	- 18	167	364	218	- 60	213
India	4	- 99	101	4	- 99	50	232	130	0	- 2
Indonesia	0	33	- 7	0	11	- 10	38	- 11	- 65	-93
Italy	- 11	- 51	7	16	- 3	191	396	278	- 120	201
Japan	0	- 25	21	3	80	98	270	148	218	178
Korea	0	39	12	24	78	92	296	175	- 43	108
Mexico	0	- 16	8	1	0	44	112	103	- 71	18
Russia	0	- 34	2	0	- 33	2	49	5	- 158	- 25
S. Arabia	0	- 68	-13	0	- 68	- 26	- 46	- 159	0	- 88
S. Africa	0	79	90	0	79	107	204	101	0	75
Turkey	0	20	0	5	14	43	219	74	- 133	111
UK	20	- 35	53	37	73	176	341	285	- 103	93
US	0	0	10	0	0	39	71	46	- 19	33
simple average	**2**	**2**	**28**	**9**	**20**	**76**	**193**	**105**	**-20**	**69**

b. For light-duty vehicles. c. For fuels used in residential buildings.

The IMF offered a comparison between carbon taxes and EU ETS identifying a higher number of advantages in a carbon tax instrument (see table 13). A carbon tax aims to put a price on carbon by setting a tax rate on the emissions of carbon content of fossil fuels used. ETS aim to incentivize polluters to reduce emissions and provide certainty about the source of long-term investment in alternative technologies (Stavins, 2022). The EU ETS aims to trade reductions in GHG emissions. Compliance bodies hold emissions allowances that correspond to their emissions. They have the opportunity to retain reserve quotas or purchase them from others. The market price of CO_2eq shifts the allocation of resources away from emissions-intensive goods (Quemin, 2022).

For example, the report commented that carbon taxes can provide certainty over future emissions prices, revenues accrue automatically to finance ministries and they easily build off existing fuel tax collection. As regards ETS, it was noted that they help achieve emissions targets with more certainty and are a more natural instrument where mitigation policy is under the purview of environment ministries. However, it was also noted that price stability mechanisms in existing EU ETS have not prevented price volatility, they are not practical in some capacity-constrained countries and incorporating other sectors through offsets may led to increased emissions.

Table 13. Summary Comparison of Carbon Taxes and ETSs. Source: Parry et al., 2022

Design issue	Instrument	
	Carbon tax	ETS
Administration	Administration is more straightforward (for example, as extension of fuel taxes)	May not be practical for capacity constrained countries
Uncertainty: price	Price certainty can promote clean technology innovation and adoption	Price volatility can be problematic; price floors, and cap adjustments can limit price volatility
Uncertainty: emissions	Emissions uncertain but tax rate can be periodically adjusted	Certainty over emissions levels
Revenue: efficiency	Revenue usually accrues to finance ministry for general purposes (for example, cutting other taxes, general investment)	Free permit allocation may help with acceptability but lowers revenue; tendency for auctioned revenues to be earmarked
Revenue: distribution	Revenues can be recycled to make overall policy distribution neutral or progressive	Free allowance allocation or earmarking may limit opportunity for desirable distributional outcomes
Political economy	Can be politically challenging to implement new taxes; use of revenues and communications critical	Can be more politically acceptable than taxes, especially under free allocation
Competitiveness	Border carbon adjustment more robust than other measures (for example, threshold exemptions, output-based rebates)	Free allowances effective at modest abatement level; border adjustments (especially export rebate) subject to greater legal uncertainty
Price level and emissions alignment	Need to be estimated and adjusted periodically to align with emissions goals	Alignment of prices with targets is automatic if emissions caps consistent with mitigation goals
Compatibility with other instruments	Compatible with overlapping instruments (emissions decrease more with more policies)	Overlapping instruments reduce emissions price without affecting emissions though caps can be set or adjusted accordingly
Pricing broader GHGs	Amenable to tax or proxy taxes building off business tax regimes; feebate variants are sometimes appropriate (for example, forestry,	Less amenable to ETS; incorporating other sectors through offsets may increase emissions and is not cost effective
Global coordination regimes	Most natural instrument for international carbon price floor	Can comply with international price floor; mutually advantageous trades from linking ETSs but does not meet global emissions requirements

Source. IMF staff.
Note: Green indicates an advantage of the instrument; orange indicates neither an advantage nor disadvantage; red indicates a disadvantage of the instrument.

Returning to the level of carbon prices, the report by Baresic et al. (2022) that relies on the various scenarios and techno-economic models outlined by Smith et al. (2019) ascertain the carbon price levels required to fulfil IMO's ambition levels. Smith et al. (2019) elaborate on the assumptions underpinning these scenarios and the modelling approach. Two global scenarios are considered, aiming for a 50% and 100% reduction in absolute emissions by 2050, respectively. According to Baresic et al. (2022): "in order to achieve 50% GHG emissions reduction by 2050 compared to 2008 (-50% scenario), the carbon price level averages

\$173/tonne CO_2. For a 2050 target of full decarbonization (-100% scenario), the average carbon price would only need to be slightly higher, around \$191/tonne CO_2. In both scenarios, according to the model, the price level begins at \$11/tonne CO_2 when introduced in 2025 and is ramped up to around \$100/tonne CO_2 in the early 2030s at which point emissions start to decline. The carbon price then further increases to \$264/tonne CO_2 in the -50% scenario, and to \$360/tonne CO_2 in the -100% scenario."

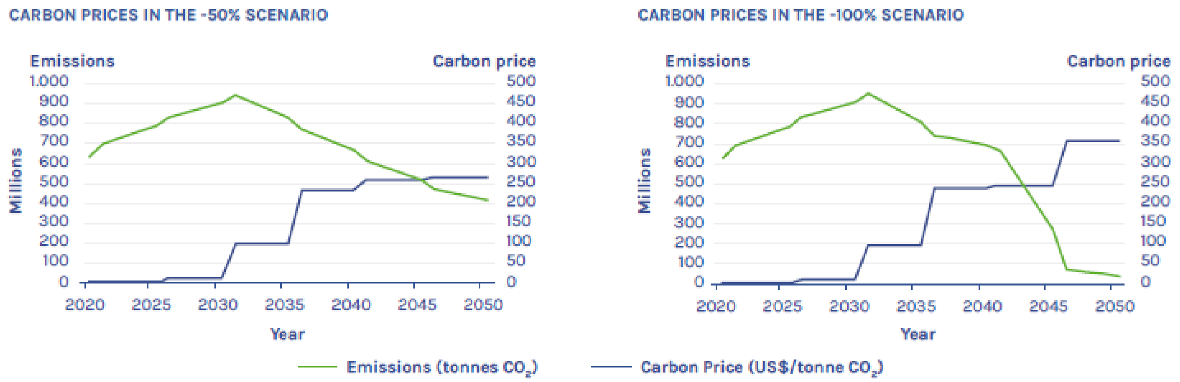


Figure 38. Carbon prices in different scenarios. Source: Smith et al., 2019

According to Baresic et al. (2022):

> *"Carbon prices could be lower than the model estimates if revenues generated by the MBM are 'recycled' to further support decarbonization of shipping, for example by subsidising the deployment of zero-emission fuels and technologies. If all MBM revenue was recycled to support shipping decarbonization, in theory, this could lower the carbon price level by up to half (but this would mean no revenue use for enabling an equitable transition and addressing disproportionately negative impacts on States). Depending on the level of revenue recycling, an MBM with global scope in the -100% scenario could be designed to have a carbon price level averaging between \$96-191/tonne CO_2 and reaching a maximum of between \$179-\$358/tonne CO_2* (see figure 39). *In reality, the carbon price would likely be somewhere in this range, so that more revenue can be used to enable an equitable transition."*

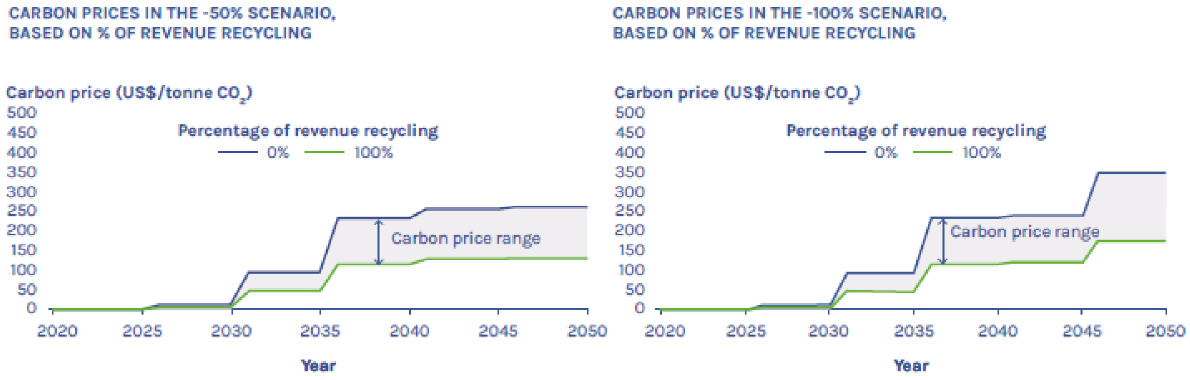


Figure 39. The carbon price trajectories and their associated emissions trajectories. Source: Baresic et al., 2022

Figure 40 below indicates that, as the carbon price increases over time, the amount of revenue that can be collected could increase significantly by the mid-2030s. From then on, however, revenues decrease gradually as the model anticipates that more and more shipowners will opt for zero emission fuels, meaning that they do not need to pay carbon prices and hence less revenue is collected. The figures give the upper and lower limits for the range of revenue that can be collected from a carbon pricing mechanism based on the same scenarios already used above.

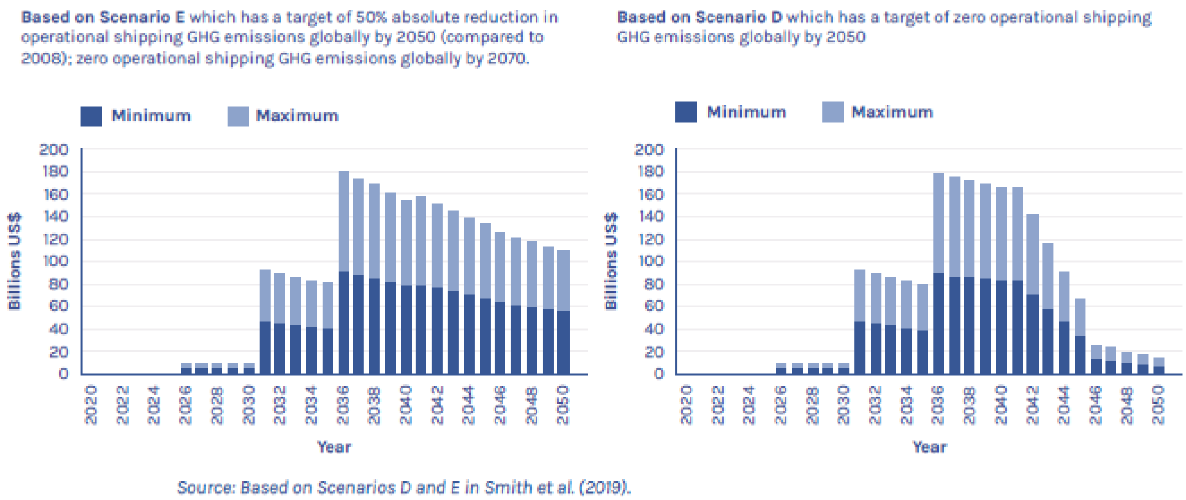


Figure 40. Future revenue ranges from carbon pricing, based on % of revenue recycling for two decarbonization scenarios. Source: Smith et al., 2019

3.2.5 Developing countries

Developing countries have significantly contributed to global maritime trade, managing 55% of exports and 61% of imports. Traditionally focused on exporting raw materials, a recent shift towards manufacturing and consumption has resulted in imports surpassing exports since 2017. During this period, developed countries accounted for 44.9% of exports and only 39.0% of imports (UNCTAD, 2022).

In late 2020 and early 2021, container shortages, port congestion and disruptions led to exceptionally high container freight rates, especially on routes between China and Europe and China and the United States. The Shanghai Containerized Freight Index (SCFI) reflected this surge, with rates increasing from below $1,000/TEU in June 2020 to $7,395/TEU by July 2021. This increase also affected developing regions such as South America and Africa (UNCTAD, 2022).

Certain developing countries, SIDS, and LDCs may require assistance to address rising maritime costs, mitigating potential adverse impacts on their income and trade activities (IMO, 2021a; IMO, 2021b).

Expense allocation in international trade reveals that developed countries spend about 11% of import value on international transport and insurance costs. In contrast, LLDCs allocate 19%, LDCs 21%, and SIDS nearly 22% (UNCTAD, 2017) (figure 41).

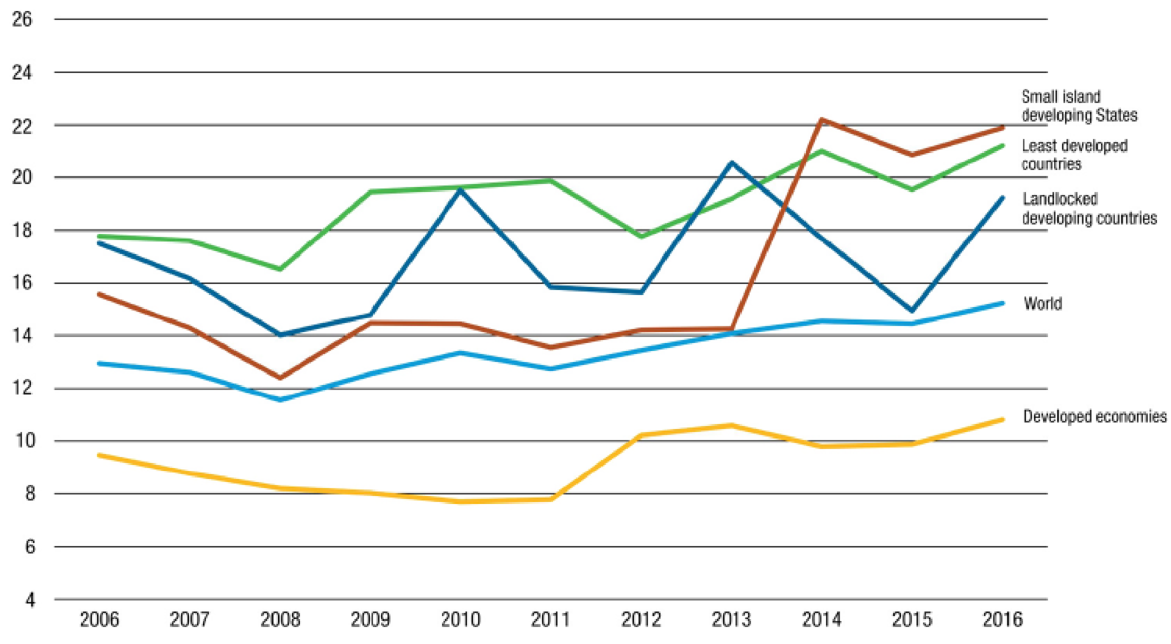


Figure 41. Transport and insurance costs of international trade, 2006–2016 (percentage share of value of imports). Source: UNCTAD, 2017

Despite increased participation in global seaborne trade, developing countries, accounting for 60% of loaded goods and 63% of unloaded goods globally in 2017, face challenges such as low maritime connectivity and inefficient port services, significantly impacting SIDS and LDCs (UNCTAD, 2017).

Rojon et al. (2021) highlight that developing countries, especially SIDS and LDCs, consistently face substantial transport costs, hindering active participation in global trade. Obstacles, including being landlocked or distant from major economic centres, coupled with low trade volumes and imbalances, contribute to increased transportation expenses. While policymakers have limited control over certain factors, numerous opportunities exist to address and alleviate transport costs through targeted international, regional, national or corporate interventions.

UNCTAD recommendations stress that developing countries need support in building more robust, resilient and sustainable supply chains. Transport and trade facilitation measures should expedite the transition to smart and eco-friendly trade logistics, emphasizing improvements in transport infrastructure, ports, hinterlands and logistics services overall (UNCTAD, 2022).

3.2.6 SIDS and LDCs

3.2.6.1 General global comparisons

Most SIDS experience significant trade imbalances, relying heavily on imports with exports being limited. Table 14 shows the imports and exports of merchandise for SIDS and highlights that, besides some exceptions, import values in 2017 significantly exceeded export values.

Table 14. Imports and exports of merchandise in 2017 (percentage of GDP). Source: Rojon et al., 2021

Region/country	Imports	Exports	Region/country	Imports	Exports
Caribbean			**Pacific**		
Antigua and Barbuda	33.6%	2.5%	Fiji	45.2%	17.9%
Bahamas	25.6%	4.7%	Kiribati	70.6%	8.2%
Barbados	32.1%	9.8%	Marshall Islands	43.3%	19.3%
Dominica	38.1%	2.3%	Micronesia (Federated States of)	50.6%	12.7%
Grenada	37.3%	2.7%	Nauru	32.1%	17.9%
Jamaica	39.3%	8.8%	Palau	55.1%	2.2%
Saint Kitts and Nevis	31.0%	5.0%	Samoa	43.2%	5.4%
Saint Lucia	36.1%	7.0%	Solomon Islands	47.7%	41.7%
Saint Vincent and the Grenadines	41.7%	5.4%	Timor-Leste	22.3%	0.9%
Trinidad and Tobago	30.7%	38.9%	Tonga	46.9%	3.8%
Average	34.5%	8.7	Tuvalu	60.5%	0.5%
			Vanuatu	42.1%	5.3%
Indian Ocean			Average	46.6%	11.3%
Comoros	23.6%	3.6%			
Maldives	49.8%	6.7%	**West Africa**		
Mauritius	39.6%	17.7%	Cabo Verde	44.6%	2.8%
Seychelles	86.6%	36.4%	Sao Tome and Principe	40.2%	4.1%
Average	49.9%	16.1%	Average	42.4%	3.5%

"Time in port" is an indicator for a port's efficiency and trade competitiveness. Two indicators of performance and efficiency of ports across the world are the 'Efficiency of Seaport Services' indicator (Global Competitiveness Index, 2019) and the 'median time in port' indicator (UNCTAD, 2020), see table 15. They show that the efficiency of seaport services is highest and the median time ships spend in port lowest for developed countries. Developing economies score lower on both indicators, with LDCs scoring lowest.

Table 15. Indicators of port performance and efficiency for different economic groupings. Source: Rojon et al., (2021)

Development Status	Global Competitiveness Index 2019 – Efficiency of Seaport Services[b]	Median time in port (in days, for all ships, 2018)
Developed economies	4.88	1.00
Economies in transition	3.15	1.66
Developing economies	3.82	1.54
LDCs	3.00	2.35
SIDS	4.24 (majority of SIDS not covered)	1.43

[b] Response to the survey question "In your country, how efficient (i.e. frequency, punctuality, speed, price) are seaport services ferries, boats)?" [1 = extremely inefficient, among the worst in the world; 7 = extremely efficient, among the best in the world].

Figure 42 provides an overview of the average transportation cost per unit for SIDS in comparison to the rest of the world. The analysis categorizes the data into five equal distance groups between 1991 and 2007. There are two main conclusions that can be drawn from this analysis. Firstly, when exporting to the rest of the world, Pacific SIDS encounter an average transportation cost that is 6% higher than the rest of the world, regardless of the distance to the importing country. In other words, the cost to transport the same unit of a product is 21% higher compared to the rest of the world when the importing country is located further than the median distance of 11,789 km. Secondly, there has been a decrease in average transportation costs per unit over time. For the rest of the world, these costs have decreased by 11%, while for SIDS the decrease is more significant at 32%. It is worth noting that the decline in transportation costs is more pronounced for SIDS than for the rest of the world, specifically for shorter trading distances. This could be attributed to the improved infrastructure in SIDS countries which has facilitated their increased involvement in global trade in the past thirty years. Given this context, Rojon et al. (2021) concluded that the implementation of a carbon price may potentially result in an increase in maritime transportation costs.

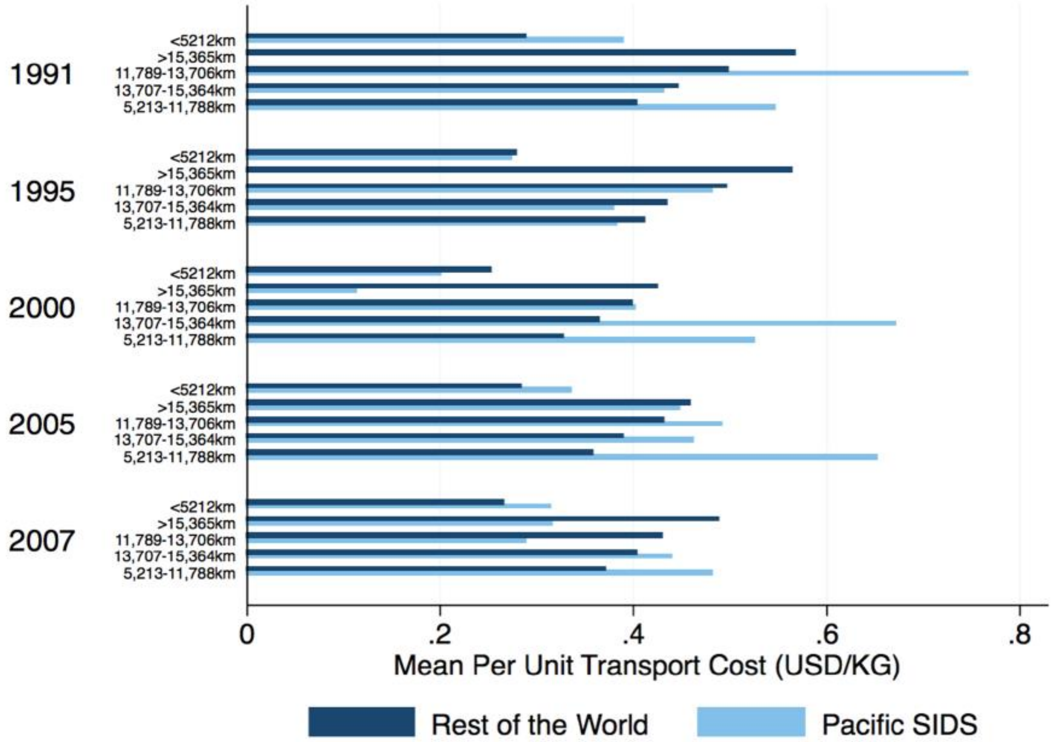


Figure 42. Mean transport costs for Pacific SIDS compared to the rest of the world. Source: Rojon et al., 2021

3.2.6.2 Pacific SIDS maritime connectivity

SIDS - Routes and service providers

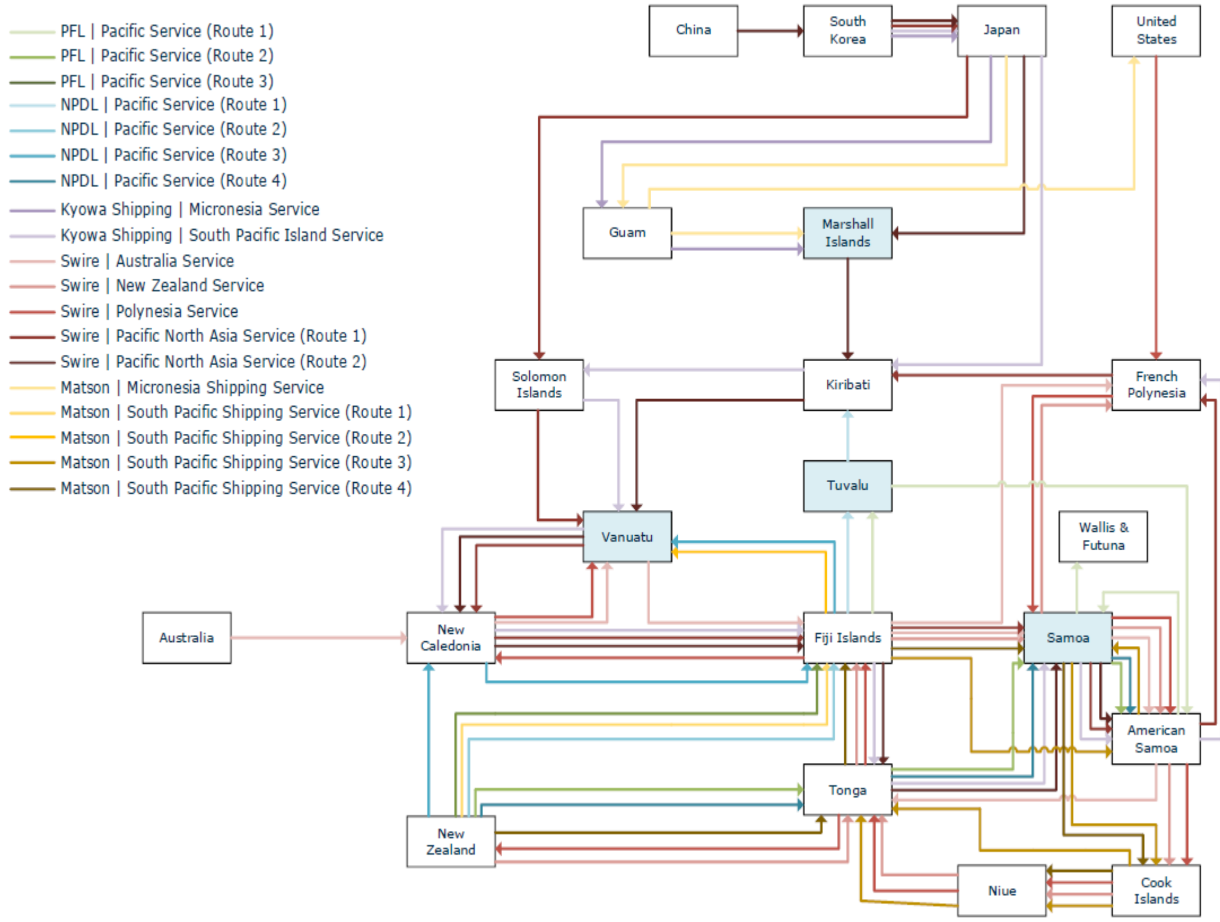


Figure 43. PIC route map. Source: UNESCAP, 2022

Figure 43 shows routes and services providers for SIDS in terms of maritime connectivity while the map in figure 44 presents the geographical setting of the ASEAN (yellow) and Pacific SIDS (red) and their Liner Shipping Connectivity Index (LSCI) levels in 2019 (Q2). It shows that ASEAN countries are concentrated in a small area and the Pacific SIDS are widely dispersed.

Both groups of countries have contrasting levels of maritime connectivity. Some countries benefit from excellent connectivity, utilizing strategic locations to promote trade. However, other countries face limited connectivity due to geographic restrictions. The disparity highlights the significance of maritime connectivity for global trade and development.

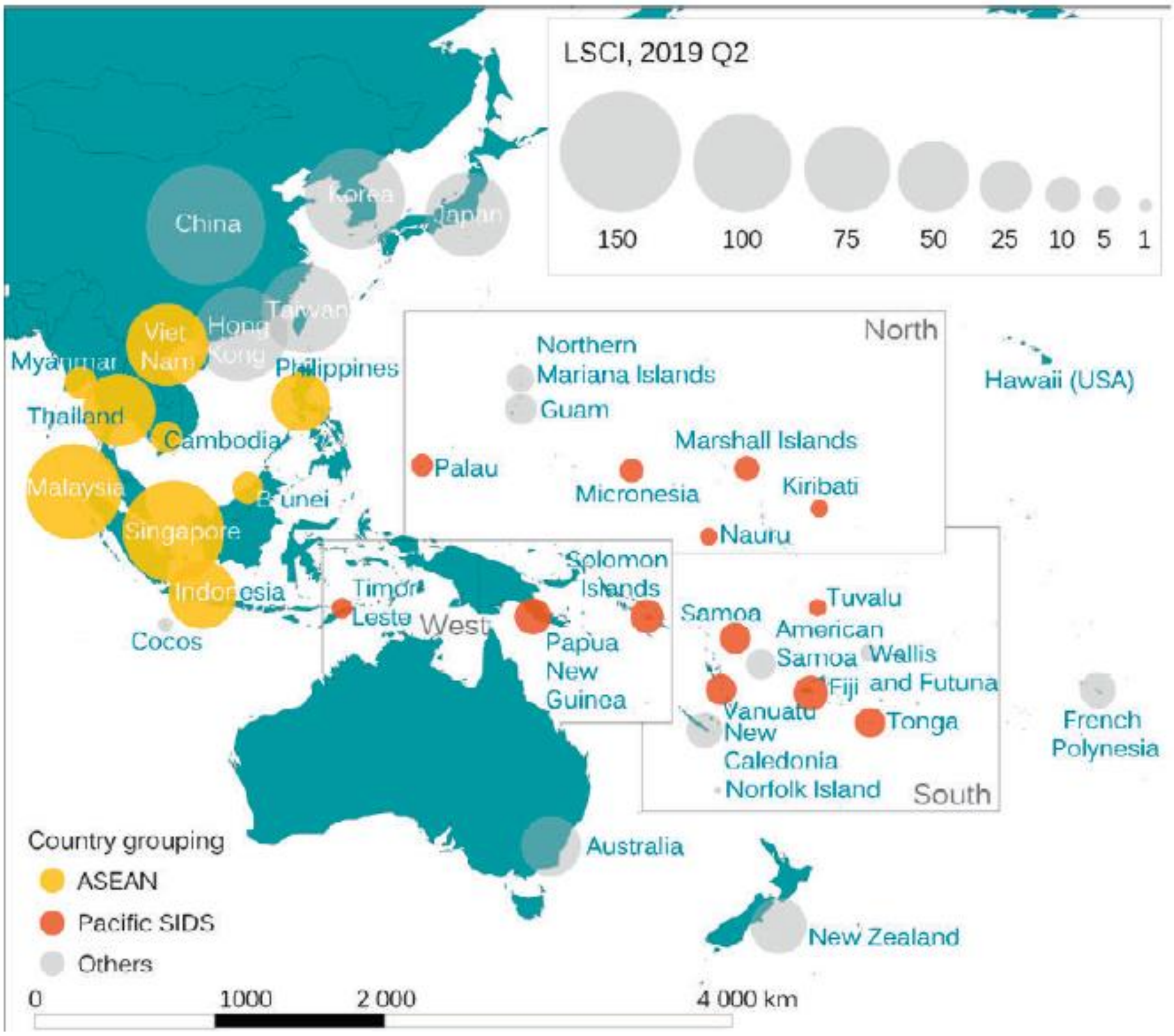


Figure 44. Countries covered in this analysis: ASEAN members and Pacific SIDS, 2019 Q2. Source: UNCTAD – UNESCAP, 2022

Pacific SIDS are remote in terms of distance to their nearest neighbours in comparison with SIDS in the Caribbean and Africa. This is illustrated in figure 45 which also shows that the differences in maritime connectivity are relatively small between Pacific SIDS compared with SIDS from other regions (UNCTAD, 2022).

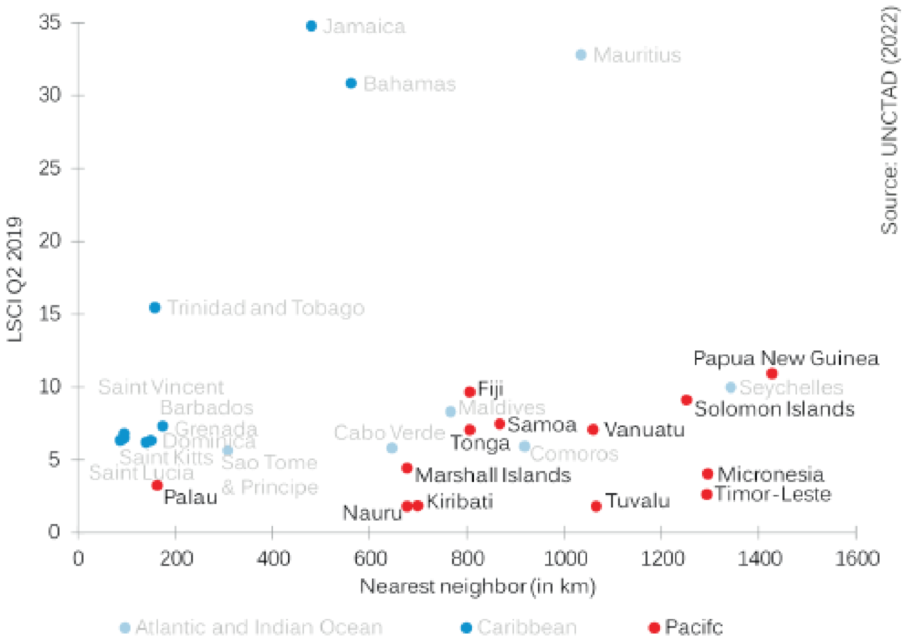


Figure 45. SIDS remoteness vs maritime connectivity. Source: UNCTAD, 2022

The financial crisis of 2008/2009 seems to have heavily impacted the maritime connectivity of several Pacific SIDS (see figure 46 and figure 47). Here, the pre-crisis levels were only recovered by 2013/2014. But, as the graphs illustrate, the trend has been one of stagnation and even decline.

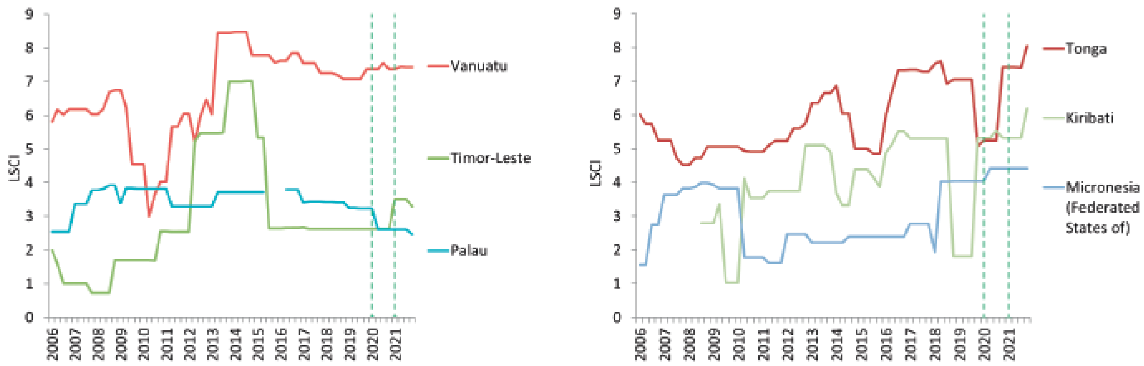


Figure 46. Evolution of the LSCI in selected Pacific SIDS, 2006-2021. Source: UNCTAD, 2022

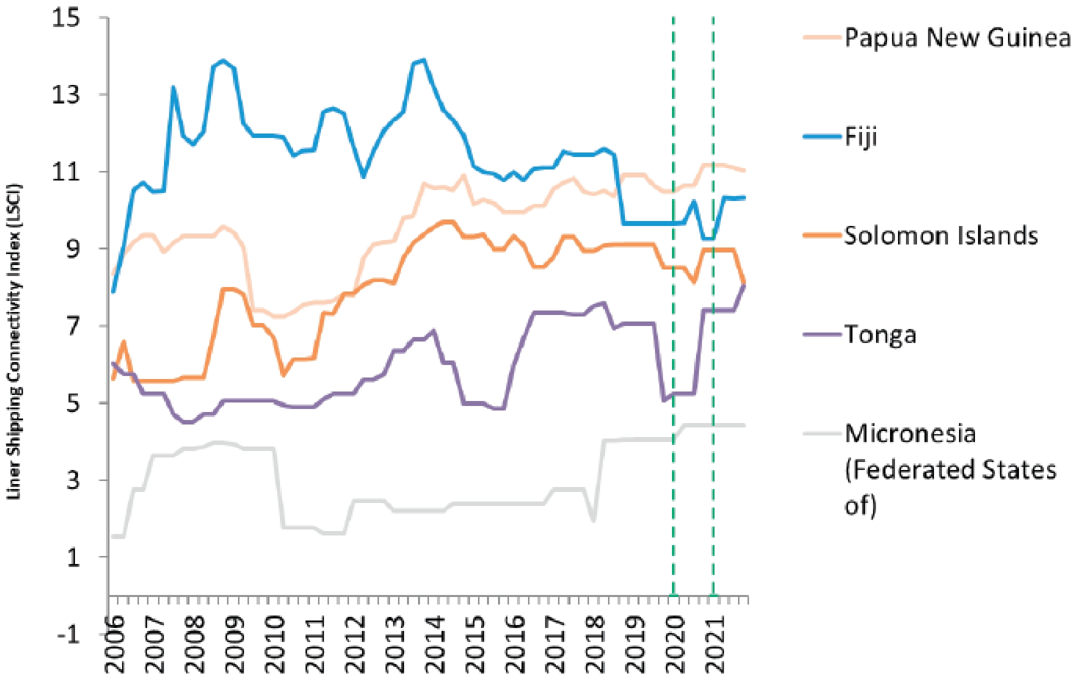
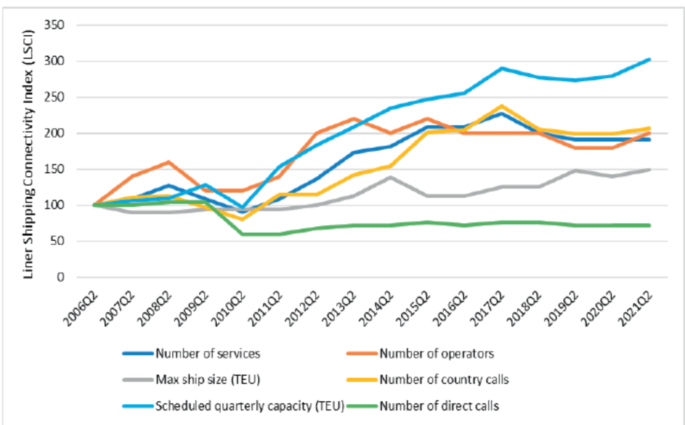
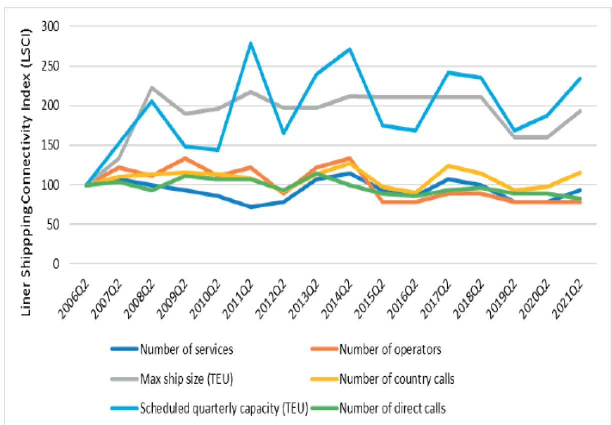


Figure 47. Evolution of the LSCI in selected Pacific SIDS, 2006-2021 (1/2). Source: UNCTAD, 2022

UNCTAD (2022) report that the "*Pacific SIDS are generally ranked at the bottom of the Country LSCI, with the only country to report a double digit LSCI in 2019 Q2 being Papua New Guinea, and Nauru, Tuvalu and Kiribati within the bottom 10 countries in the same year quarter. Analysing the second quarter of all the years between 2006 and 2021, we also notice that some of these countries do not always have a LSCI meaning that there have been periods in which some countries were not directly served by shipping lines*" (See figure 48 and figure 49).





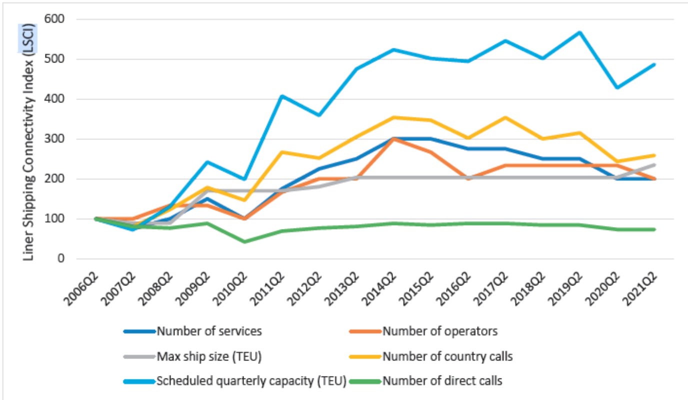
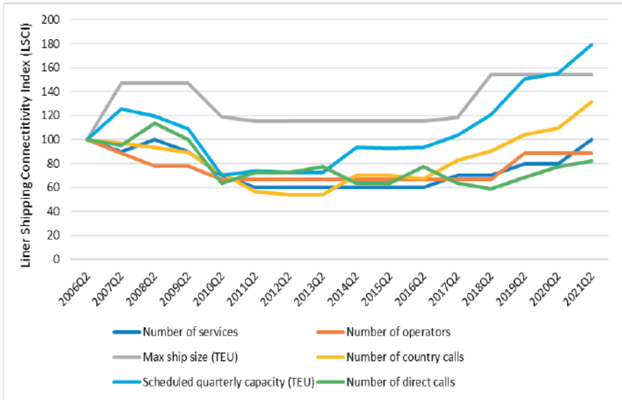
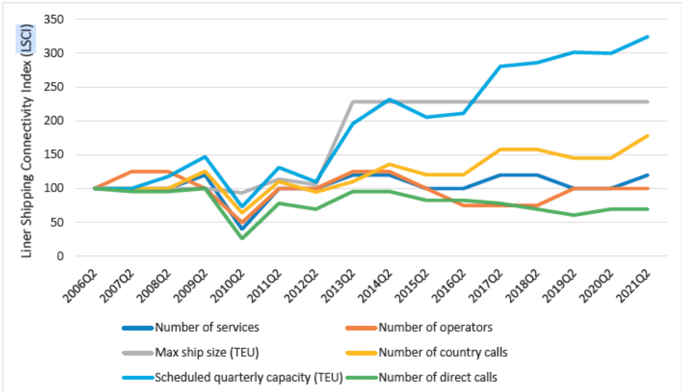
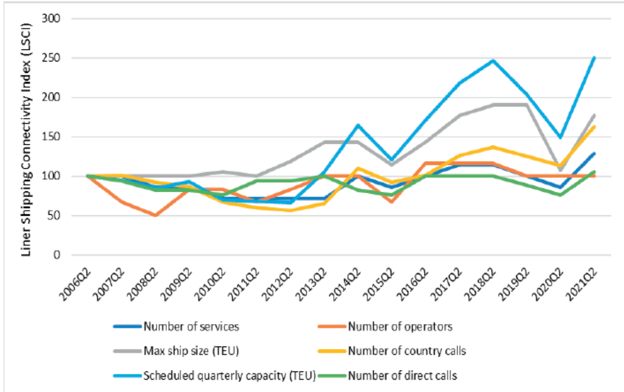
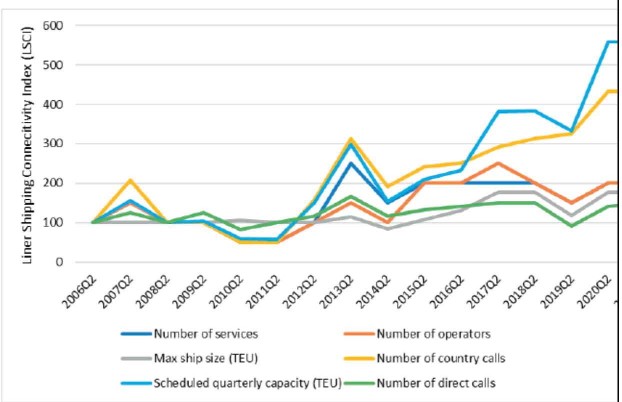
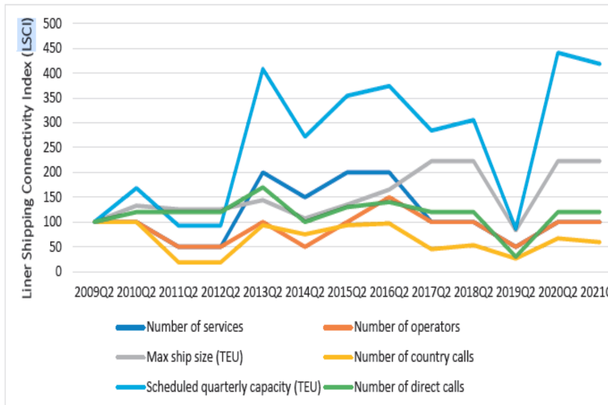
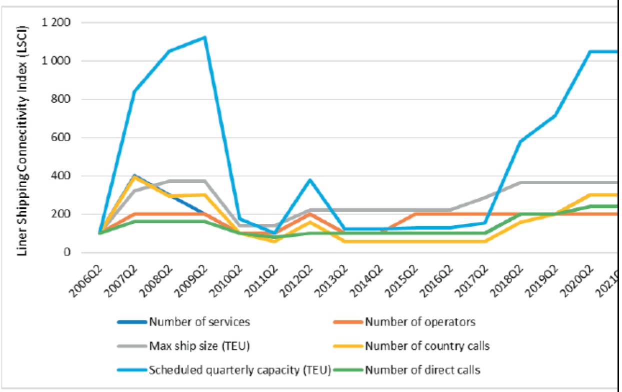
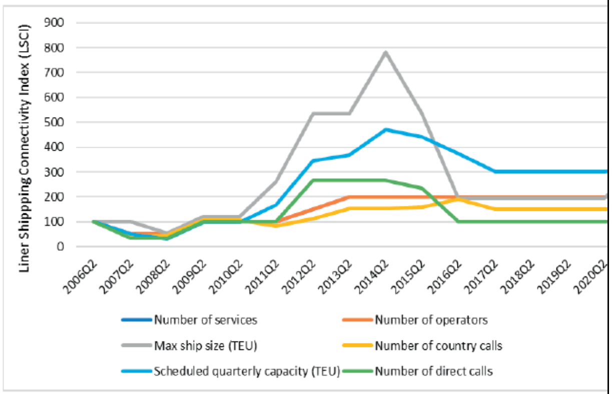
Papua New Guinea	Fiji
	
Solomon Islands	Samoa
	
Vanuatu	Tonga

Figure 48. LSCI components, Pacific SIDS. Source: UNCTAD, 2022.

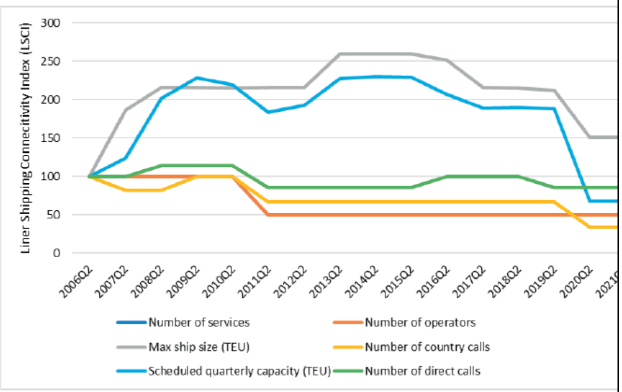
	
Marshall Islands	Kiribati



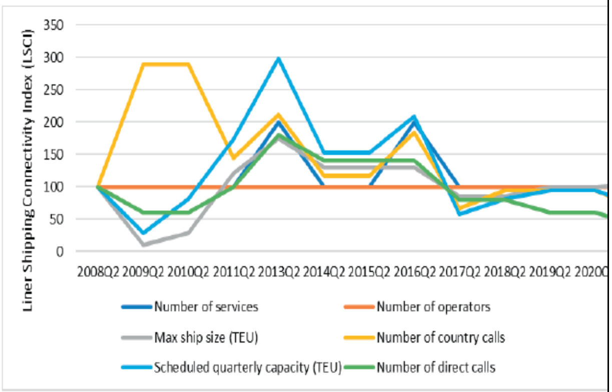
Micronesia



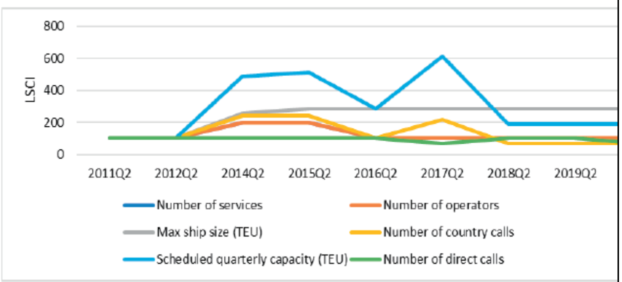
East Timor



Palau



Tuvalu



Nauru

Figure 49. LSCI components, Pacific SIDS. Source: UNCTAD, 2022.

Figure 50 shows the best intra-regional connections within the Liner Shipping Bilateral Connectivity Index (LSBCI) in 2019 and that the links within the same subregion are generally stronger than those between subregions. Moreover, it shows that the only region which is well connected to all the sub-regions in the Pacific SIDS is East-Asia (2019 data). The North Pacific is poorly connected with all the other regions, including ASEAN and Oceania.

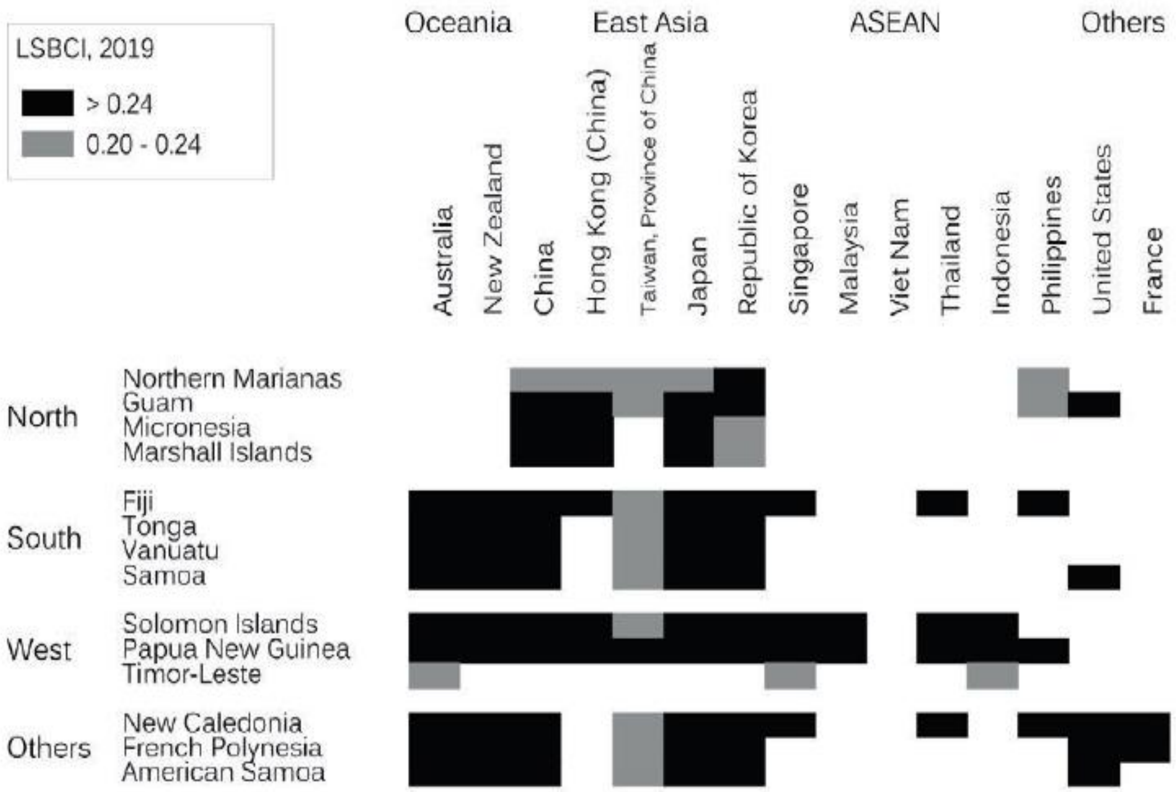


Figure 50. LSBCI of the Pacific SIDS. INTRA-regional (2019). Source: UNCTAD, 2022

Figure 51 illustrates the significant changes in intra-regional connectivity from 2006 to 2019 in a comprehensive manner. It effectively highlights how the Marshall Islands have strengthened their relationships with neighbouring countries. Moreover, it underscores the notable declines in links between the North Pacific and the South Pacific, impacting all countries except Fiji. The North Pacific (Micronesia and the Marshall Islands) also experienced enhanced connections with the Western Pacific (Solomon Islands and Papua New Guinea). In contrast, the connections between the Marshall Islands and the "Others" (New Caledonia, French Polynesia, and American Samoa) witnessed a decrease. Furthermore, there were alterations in connectivity between the West Pacific and the South Pacific. Notably, Solomon Islands and Papua New Guinea observed improved connectivity with Fiji, while Papua New Guinea's connections with Samoa and French Polynesia declined. These advancements in Fiji's connectivity with countries in other subregions emphasize its emerging role as the primary transhipment base in the South.

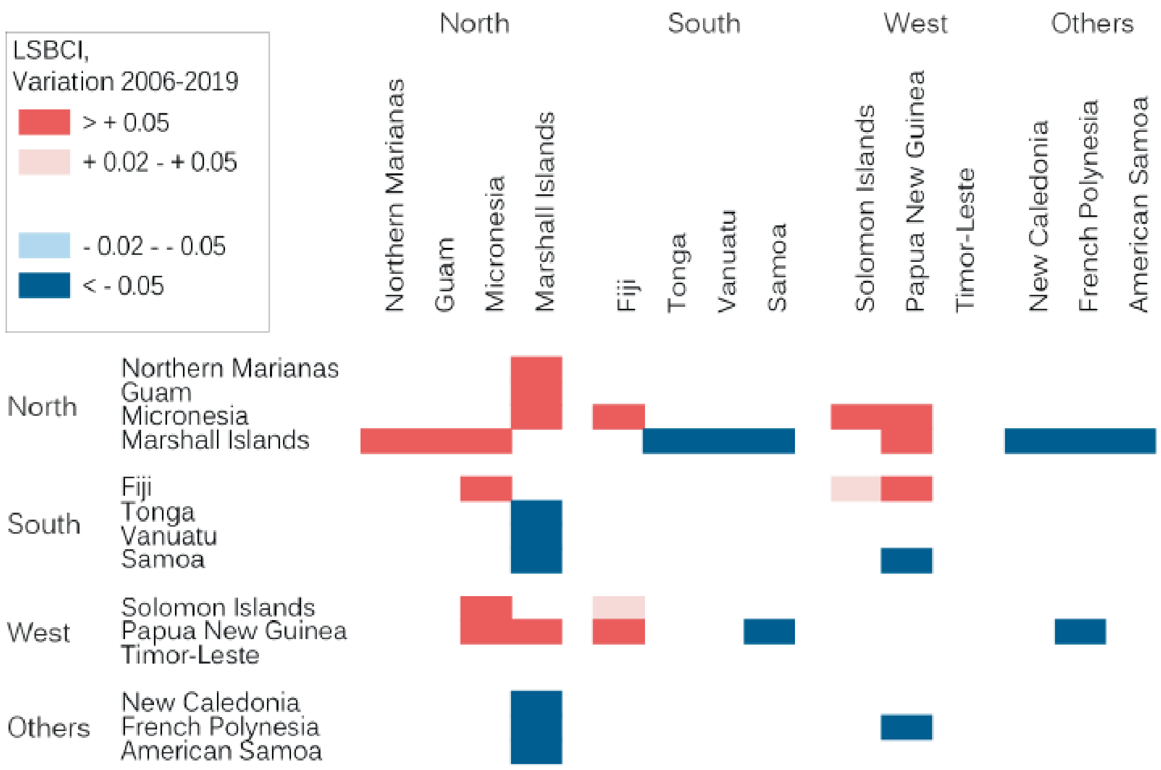


Figure 51. LSBCI of the Pacific SIDS. INTRA-regional (Variation 2006-2019). Source: UNCTAD, 2022

3.2.6.3 Pacific SIDS Port LSCI ranking

Within ASEAN, most of the country pairs are directly connected, as illustrated by figure 52. Between 2006 and 2021 several new links were created while others disappeared.

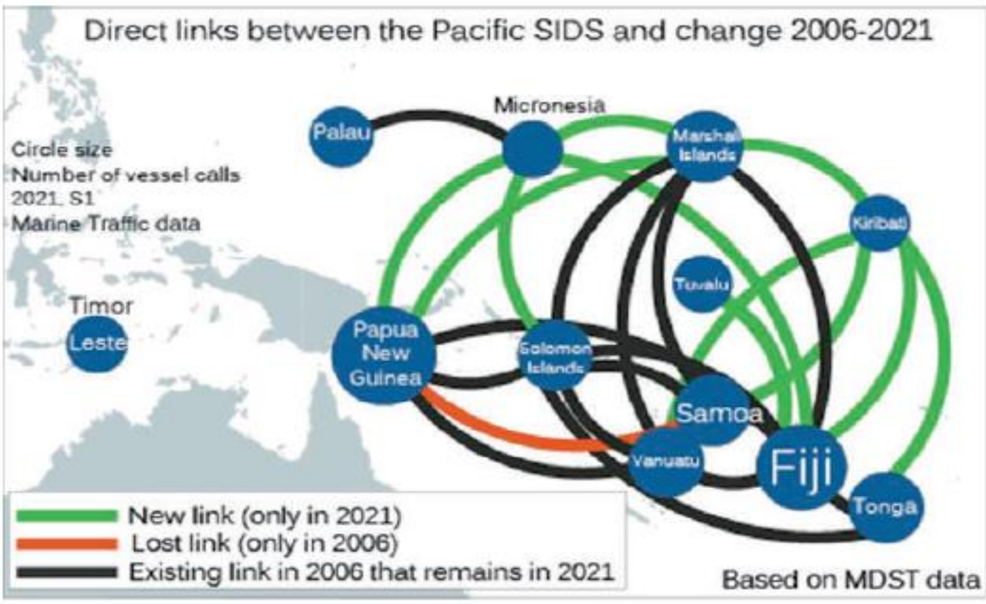


Figure 52. Direct links between Pacific SIDS. Circle size reflects number of calls (2021 S1). Source: UNCTAD, 2022

Table 16 shows the best and worst connected SIDS ports, by port LSCI.

Table 16. Pacific SIDS best and less connected ports, Q2 2020 and Q1 2022. Source: UNCTAD – UNESCAP, 2022

Pacific SIDS best-connected ports		Pacific SIDS less connected ports	
2020 Q2	2022 Q1	2020 Q2	2022 Q1
i. **Papua New Guinea, Lae (11)**	1. **Papua New Guinea, Lae (11.6)**	i. Papua New Guinea, Wewak (3.3)	1. Solomon Islands, Noro (2.7)
ii. **Fiji, Suva (8.9)**	2. **Fiji, Suva (9.4)**	ii. Timor-Leste, Dili (2.6)	2. **Marshall Islands, Kwajalein (2)**
iii. **Fiji, Lautoka (8.8)**	3. **Fiji, Lautoka (9.3)**	iii. **Marshall Islands, Kwajalein (2.5)**	3. **Micronesia (Federated States of), Truk (2)**
iv. **Solomon Islands, Honiara (7.5)**	4. **Papua New Guinea, Port Moresby (9.1)**	iv. **Micronesia (Federated States of), Yap (2.1)**	4. **Micronesia (Federated States of), Yap (2)**
v. **Papua New Guinea, Port Moresby (7.5)**	5. Samoa, Apia (7.6)	v. **Palau, Koror (2.1))**	5. **Palau, Koror (2)**
vi. **Samoa, Apia (6.9)**	6. **Solomon Islands, Honiara (7.5)**	vi. **Micronesia (Federated States of), Truk (2)**	6. Tonga, Vavau (1.8)
vii. Vanuatu, Port Vila (7)	7. American Samoa, Pago Pago (7.1)	vii. **Papua New Guinea, Alotau (1.6)**	7. **Papua New Guinea, Alotau (1.6)**
viii. Papua New Guinea, Lihir Is (6.7)	8. Tonga, Nukualofa (6.9)	viii. **Papua New Guinea, Buka (1.6)**	8. **Papua New Guinea, Buka (1.6)**
ix. **Papua New Guinea, Madang (6.7)**	9. **Papua New Guinea, Madang (6.9)**	ix. **Tuvalu, Port Funafuti (1.6)**	9. **Tuvalu, Port Funafuti (1.4)**
x. American Samoa, Pago Pago (6.7)	10. **Papua New Guinea, Rabaul (6.7)**	x. Nauru, Nauru (1.6)	10. Papua New Guinea, Oro Bay (1.1)

Based on figure 53, in Solomon Islands, the port of Honiara holds significant importance with a PLSCI of approximately 8, indicating an almost twofold increase since 2006. The newer container port in the country, Noro, is unable to surpass a PLSCI of 5. Shifting our focus to Papua New Guinea, the ports of Lae and Port Moresby have experienced noteworthy progress in their connectivity levels from 2006 to 2019, albeit with some fluctuations. However, the outbreak of COVID-19 seems to have magnified the divergent trends of these two ports. Since 2020, Lae has achieved a score of approximately 12, while Port Moresby has remained around 8. In the Northern Pacific region, the ports exhibit comparatively lower scores. Among SIDS, the top-performing port is Majuro which attained a score of 6 in Q4 2021. The Micronesian ports, Kosrae, Pohnpei, Truk and Yap, have scores ranging from 2 to 3.5. Yap has witnessed a significant decline over the period of 2006 to 2021. Apra and Honolulu serve as crucial transhipment hubs for ports in the subregion, with the latter outperforming since the COVID-19 outbreak in 2020. Moving on to the South Pacific ports, their connectivity levels are higher compared to those in the North Pacific, yet slightly lower than Lae (West). In Fiji, the ports of Suva (experiencing a decline) and Lautoka (making progress) converge to similar connectivity levels during the period of 2006 to 2019. However, Apia and Nukuoalofa have remained stagnant (UNCTAD – UNESCAP, 2022).

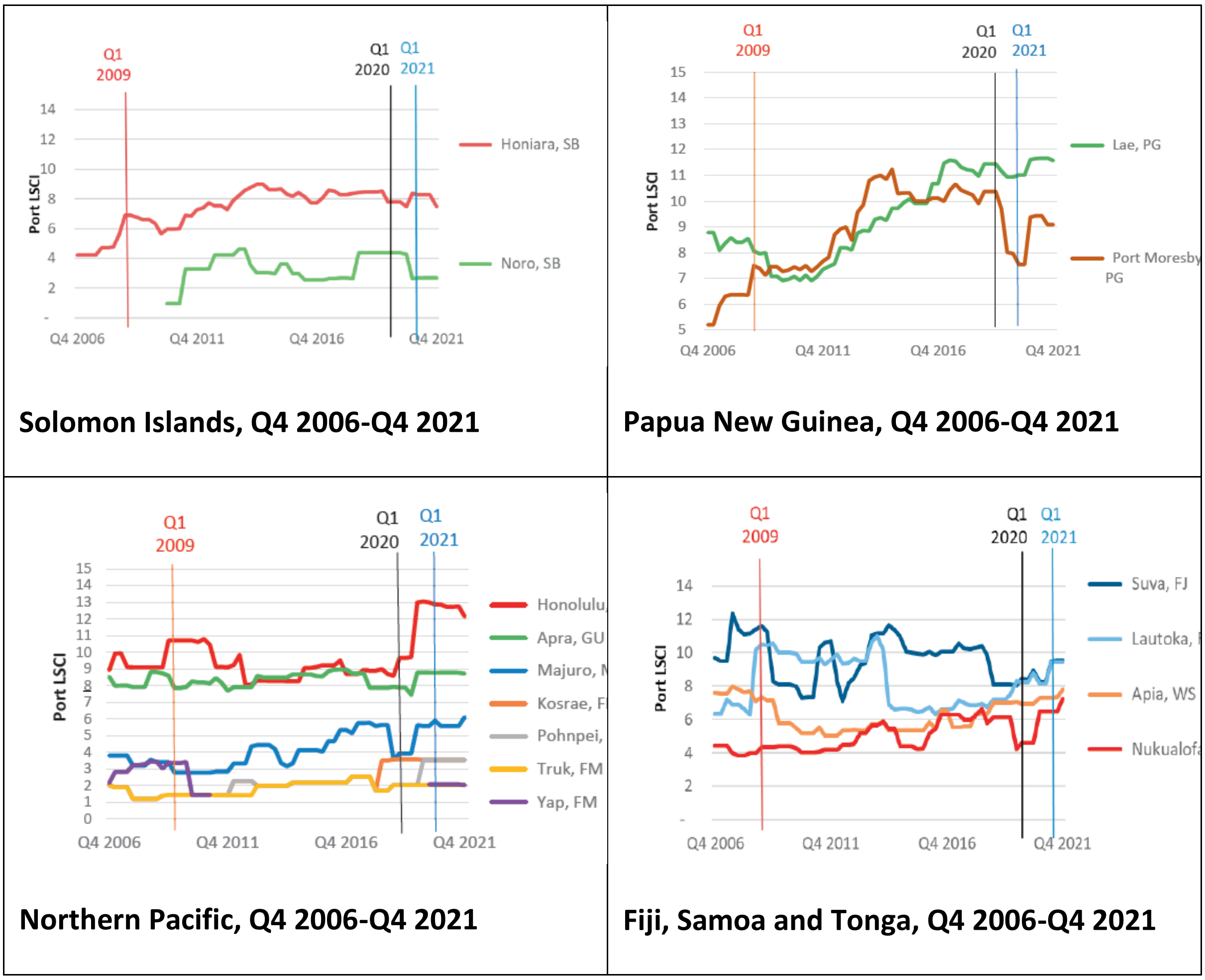


Figure 53. PLSCI of main Pacific SIDS ports, UNCTAD – UNESCAP, 2022

3.2.6.4 Ports and maritime connectivity in the Pacific region

Table 17 attempts to depict the Pacific SIDS port productivity ratios (average turnaround time). PRIF (2021) provided a comparison of port pricing published for Pacific Island ports. The information displayed in figure 16 regarding port productivity ratios is crucial for reference purposes. It is of utmost importance to establish a thorough definition to enable accurate comparisons among different types of ships, ports and terminals. In order to comprehend any discrepancies, a thorough examination and evaluation of the specific factors for each port could be necessary. As an illustration, the situation in Nauru highlights a vessel turnaround time that surpasses 13 days.

Table 17. Average Vessel Turnaround Time by Type of Ship, 2019-2020 (PRIF, 2021). Source: UNESCAP, 2022

Country	Passenger Ships (days)	Container Ships (days)	No. of TEU Containers
Cook Islands			8,106
FSM	0.35 days		25,234
Fiji	1.07 days	0.98 days	145,782
Kiribati	1.58 days	1.58 days	52,100
Nauru		13.25 days	5,327
Niue			3,904
Palau			16,399
PNG	1.23 days	1.30 days	338,300
RMI	0.98 days	0.97 days	30,711
Samoa	0.66 days	0.87 days	27,221
Solomon Islands	1.11 days	1.05 days	128,036
Tonga[128]	0.43 days	0.54 days	76,854
Tuvalu		2.62 days	5,150
Vanuatu	0.88 days	0.88 days	77,436

FSM = Federated States of Micronesia, PNG = Papua New Guinea, RMI = Republic of the Marshall Islands, TEU = twenty-foot equivalent unit.
Note: All data from 2019 except for Nauru (19 Aug 2019–20 Aug 2020) and Tuvalu (Jan–Oct 2020).
Sources: The Pacific Community, Geoscience, Energy and Maritime Division (data for Nauru and Tuvalu received 18 Feb 2021); and United Nations Conference on Trade and Development. Undated. Maritime Country Profiles. https://unctadstat.unctad.org/CountryProfile/MaritimeProfile/en-GB/776/index.html (accessed 27 Dec 2020).

In table 18 we see some route duration data (UNESCAP, 2022). Upon analytical examination of the routes, it is evident that the duration of a route is undeniably influenced by its distance and the locations it covers. It becomes apparent that hub-and-spoke system routes, when scrutinized from this perspective, tend to be shorter. On the other hand, milk-run-esque routes, which resemble the characteristics of a journey with multiple stops, can be substantially longer in terms of duration, often reaching two or even four times the length.

Table 18. Shipping Route & Duration (based on desk research). Source: UNESCAP, 2022

#	Shipping Route	Duration
01	PFL | Pacific Service (Route 1)	~10 Days
02	PFL | Pacific Service (Route 2)	~05 Days
03	PFL | Pacific Service (Route 3)	~07 Days
04	NPDL | Pacific Service (Route 1)	~17 Days
05	NPDL | Pacific Service (Route 2)	~06-09 Days
06	NPDL | Pacific Service (Route 3)	~16 Days
07	NPDL | Pacific Service (Route 4)	~07-10 Days
08	Kyowa Shipping | Micronesia Service	~10 Days
09	Kyowa Shipping | South Pacific Service	~49 Days
10	Swire | Australian Service	~35 Days
11	Swire | New Zealand Service	~35 Days
12	Swire | Polynesia Service	~90 Days
13	Swire | Pacific North Asia Service (Route 1)	~43 Days
14	Swire | Pacific North Asia Service (Route 2)	~62 Days
15	Matson | South Pacific Shipping Service (Route 1)	~09 Days
16	Matson | South Pacific Shipping Service (Route 2)	~07 Days
17	Matson | South Pacific Shipping Service (Route 3)	~16 Days
18	Matson | South Pacific Shipping Service (Route 4)	~30 Days

Figure 54 and table 19 provide the total TEUs trade in Pacific Island ports between 2010and 2018.

According to a report by UNCTAD in 2021, there has been a significant growth in the volume of containers handled by ports worldwide since 1972. The numbers have gone up from 6.3 million to a staggering 815.6 million twenty-foot equivalent units (TEU) in 2020. To provide some context, as shown in table 18, the 11 Pacific island states mentioned only contributed a mere 708,000 TEU, which is just 0.08% of the global volumes in 2018. This remarkable increase in maritime traffic has resulted in major changes in ports, requiring the development of larger terminals with specialized container capacity. In many cases, these transformations have led to the relocation of ports from their original positions due to limitations imposed by their proximity to urban centres.

Table 19. Total TEU Volume Statistics at PIC Ports 2010 – 2018. Source: UNESCAP, 2022

	2010	2011	2012	2013	2014	2015	2016	2017	2018
FJI	257,316	290,789	232,617	324,270	329,097	255,214	244,524	276,944	279,466
FSM	6,570	5,900	13,192	9,270	9,270	9,815	9,815	11,434	32,195
KIR	29,876	25,776	25,776	52,964	22,998	35,149	49,005	53,469	52,568
MHL	19,700	21,989	28,797	47,899	26,168	41,855	51,613	74,194	70,146
NRU		2,597	2,597	5,563	8,530	9,438	7,033	5,536	7,607
PLW	24,446	17,629	18,800	23,548	23,960	23,891	22,490	20,009	20,059
SLB	63,095	111,620	138,567	143,880	203,915	195,524	181,636	180,838	174,614
TON	48,431	57,059	67,349	74,745	69,196	50,408	84,702	107,381	105,190
TUV	1,719	9,976	5,847	24,770	13,766	13,766	15,844	6,500	6,188
VUT	18,040	64,663	60,342	122,540	141,788	120,492	115,887	114,553	106,680
WSM	22,465	21,420	23,137	24,006	27,198	27,719	27,459	27,589	27,524

Figure 54 shows information about metadata related to developing countries. According to this data, the average TEU throughput in 2018 for the 11 PIC states was 80,000 TEU. However, if we remove the two largest outlier states, Fiji and Solomon Islands, the average TEU throughput drops to 64,000 TEU. It is also important to note the imbalance between full and empty containers when looking at containerized throughput in PICs. This imbalance presents a major challenge in terms of both supply and value chain conditions.

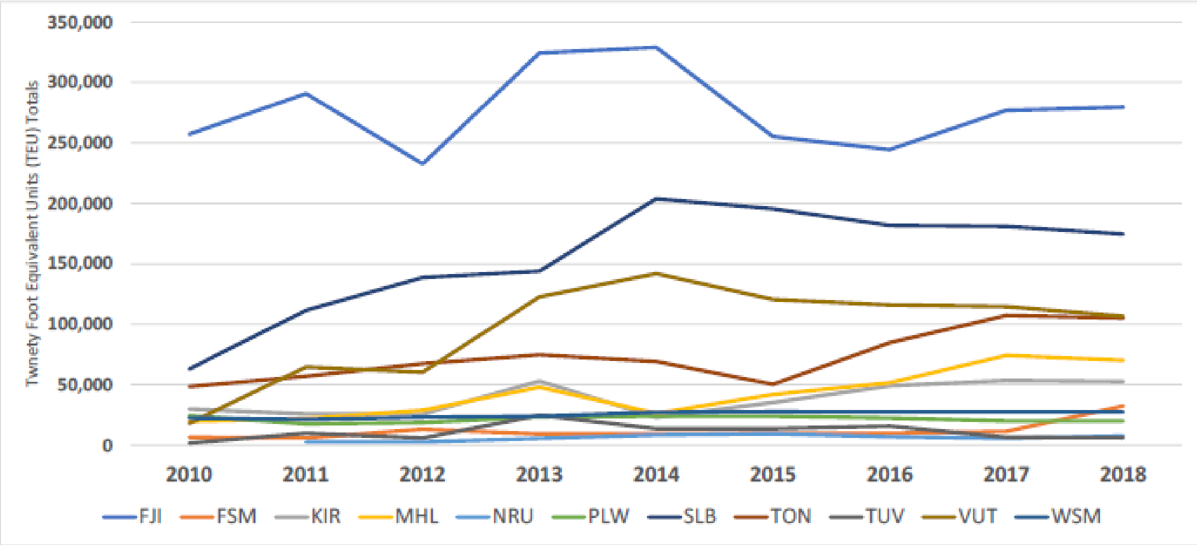


Figure 54. Total TEU Volume Chart PIC's 2010 – 2018. Source: UNESCAP, 2022.

According to data presented by PRIF (2021) in table 20, there exists a publication containing port pricing comparisons for Pacific Island ports. However, these comparisons only offer a partial representation of the vast differences in tariffs between ports and fail to effectively compare ports that are similar in nature.

Table 20. Ports tariffs in Vanuatu, Tonga, Fiji, Cook Islands and Kiribati 2021. Source: PRIF, 2021

Tariff Item	Lapetasi Port in Vanuatu		Ports Authority Ports in Tonga		Fiji Ports		Cook Islands Ports		Kiribati Ports	
	Vt	$	T$	$	F$	$	NZ$	$	A$	$
Load/Unload TEU (Full)	35,000	306.64	135 (partial)	57.23	150	72.92	247	178.75	250	193.11
Load/Unload FEU (Full)	50,000	438.06	270 (partial)	114.46	225	109.38	481	348.09	375	289.66
Load/Unload TEU (Empty)	21,000	183.99	65 (partial)	27.56	80	38.89	24.70	17.88	125	96.55
Load/Unload FEU (Empty)	35,000	306.64	151 (partial)	64.01	120	58.37	36	26.05	187.50	144.83
Berthing Charge (Container Vessel)	300 per meter per day	2.63 per meter per day	0.1296 per GT per hour	0.05 per GT per hour	2.72 per 100 GRT per hour	1.32 per 100 GRT per hour	0.41 per GRT per day	0.30 per GRT per day	5 per 100 GRT per day	6.18 per 100 GRT per day
Mooring Fee	13,000 up to 100 meters LOA or 16,000 for more than 100 meters LOA	113.90 or 140.18	0.80 per GRT	0.34 per GRT	0.286 x GRT + 1,048	0.14 x GRT + 509.47	1.29 per GRT per visit	0.93 per GRT per visit	8 per 100 GRT	6.18 per 100 GRT
Terminal/Wharfage Fee TEU (Full)	Nil	Nil	179	75.88	70	34.03	1.24 per cubic meter	0.90 per cubic meter	10 per cubic meter or tonne	7.72 per cubic meter or tonne
Terminal/Wharfage Fee FEU (Full)	Nil	Nil	358	151.77	98	47.64	1.24 per cubic meter	0.90 per cubic meter	10 per cubic meter or tonne	7.72 per cubic meter per tonne
Storage of Containers	No charge for first 5 days		No charge for first 5 days		No charge for first 3 days		No charge for first 8 days		No charge for first 21 days	

$ = United States dollars, A$ = Australian dollars, F$ = Fiji dollars, FEU = forty-foot equivalent unit, GRT = gross registered tonnage, GT = gross tonnage, LOA = length overall, NZ$ = New Zealand dollars, TEU =

Regarding the amount of port calls and port performance and the average time spent per ship, the analysis performed here is based on UNESCAP (2022) where the countries are grouped in three sections (see table 22):

- The four SIDS (listed in the first four rows);

- The other Pacific SIDS for comparison reason;
- The main countries where the shipping routes start/finish in another section, as well as the worldwide average.

When comparing the time a ship spent, the average is higher for the four SIDS compared to other similar SIDS in the region (See Table 21).

Table 21. Port calls and performance for a selection of ports. Source: UNESCAP, 2022

	# Ship Arrivals	Average time spent per ship (day)		Average Carrying Capacity per ship	
Country	**All Ships**	**All Ships**	**Container**	**DWT**	**TEU**
Vanuatu	148	0.96	1.02	15,231	1,317
Samoa	131	0.74	0.89	11,702	1,233
Tuvalu	-	-	-	-	-
Marshall Islands	47	0.97	0.97	-	1,249
Average	**108.67**	**0.89**	**0.96**	**13,466.5**	**1,266.33**
Fiji	1,973	1.08	1.02	11,161	1,362
American Samoa	109	0.98	1.00	13,164	1,247
Tonga	135	0.45	0.55	10,460	1,187
Niue	-	-	-	-	-
Cook Islands	-	-	-	-	-
French Polynesia	5,614	0.22	0.66	2,265	2,709
Guam	324	1.17	0.92	20,930	1,916
Solomon Islands	179	1.14	1.14	30,034	1,424
Average	**1,389**	**0.84**	**0.88**	**14,669**	**1,640.83**
Australia	58,474	1.51	1.41	81,621	4,774
New Zealand	12,580	1.25	0.85	31,661	3,528
Republic of Korea	73,563	0.86	0.64	23,371	3,056
Japan	259,583	0.40	0.34	14,768	1,620
United States of America	246,863	1.45	1.03	47,136	5,347
Average	**130,212.6**	**1.09**	**0.85**	**39,711.4**	**3,665**

An inventory of development partner-financed projects in PIC can be seen in table 22.

Table 22. Summary of major domestic connectivity-related projects. Source: UNESCAP, 2022

Country/ies (or Regional)	Project name	Development partner/s	Location	Start year	End year	Completed, current or future	Cost USD (millions)	Funding amount, type, source (USD)	Activity type (i.e., construction, operations, policy etc)
Regional	Preparing Projects to Enhance Transport Connectivity and Resilience in the Pacific	ADB	Fiji (Suva port), Cook Islands (airport)	2020	2025	Current	5.5	5.5 TA (only a portion on maritime)	Project preparation for infrastructure
Cook Islands	Avatiu Port Development Project	ADB	Rarotonga	2008	2015	Completed	24.6	24.6m (20.2m loan, 0.8m grant, remainder CIG)	Infrastructure construction
Federated States of Micronesia	Federated States of Micronesia Maritime Investment Project	World Bank	Kosrae, Pohnpei, Chuuk, and Yap ports	2019	2024	Current	38.5	38.5m grant	Infrastructure planning, design, construction, and rehabilitation Institutional development/ capacity building
Fiji	Fiji Ports Development Project	ADB	Suva and Lautoka Ports	1998	2007	Completed	36	16 ADB loan, 20m other financing	Infrastructure construction
	Port Security Inspection Scanner Project	China		2018			8.4	8.4m grant	Equipment purchase
	Assessment of current Suva port condition and operations – relocation	ADB	Suva	2020	2022	Current	2.3	2.3m grant	Suva port relocation assessment of new sites and cost estimates
Kiribati	The Project for Expansion of Betio Port	JICA	Tarawa	2010	2014	Completed	33.8	33.8m	Infrastructure construction
	KOIL's New Additional Fuel Storage	Taiwan	Tarawa	2012	2021	Completed	15	15m grant	Infrastructure construction
Marshall Islands	Marshall Islands Maritime Investment Project	World Bank	Majuro and outer islands	2019	2024	Current	33	33m grant	Infrastructure construction; equipment purchase; institutional development/ capacity-building
Nauru	Sustainable and Climate – Resilient Connectivity Project	ADB (with grants from Australia and GCF)	Aiwo, Nauru	2017	2022	Current	80	~ 80m (21m ADB grant, 14m Australia grant, 27m GCF grant and funding from Nauru)	Infrastructure construction; institutional strengthening
Samoa	Enhancing Safety, Security, and Sustainability of Apia Port Project	ADB	Apia	2019	2024	Current	75	75m (65m ADB grant, 13m counterpart)	Infrastructure construction; operational improvements; equipment purchase
	Enhancing Safety, Security and Sustainability of Apia Port	ADB	Apia	2018	2024	Current	75.03	62.26m grant Samoa Govt contribution 12.77m	Reconstruction of the breakwater, Acquisition of one new Tugboat, new X-Ray scanner, various superstructures, Green Port Initiatives.
	Second Development of Apia Port	JICA	Matautu Port, Apia	2015	2018	Completed	30	30m grant	Infrastructure construction, tugboat repairs and superstructures
Solomon Islands	Solomon Islands Land and Maritime Connectivity Project	ADB	Nation-wide	2021	ongoing	Current	171	171m (74.5m grant, 74.4m loan, 21.8 m Solomon Islands Government)	Infrastructure construction
	Project for Improvement of Honiara Port Facilities	JICA	Honiara	2014	2016	Completed	28	28m grant	Construction of a second international wharf and expansion of container terminal yard
Tonga	Nuku'alofa Port Upgrade Project	ADB	Nuku'alofa, Queen Salote Wharf	2020	2026	Current	50	50m (45m ADB grant, 5m counterpart)	Infrastructure construction; institutional strengthening

	X-ray Machines for the wharf and airport	China	Nuku'alofa	2019	2019	Completed	9.5	9.5m	Equipment purchase
Tuvalu	Maritime Investment in Climate Resilient Operations	World Bank	Nanumaga harbor and Funafuti port	2018	2024	Current	22.5	22.5m	Master planning; Infrastructure construction; Institutional strengthening; Contingency emergency response
	Improvement of Funafuti Port	JICA	Funafuti	2007	2009	Completed	5.6	5.6m grant (930 million yen)	Infrastructure construction
Vanuatu	Luganville Wharf Redevelopment	China	Espiritu Santo	2013	2017	Completed	93.4	80m concessional loan	Infrastructure construction
	Port Vila Lapetasi International Wharf Development Project	Japan/JICA	Port Vila	2012	2017	Completed	70	70m concessional loan	Infrastructure construction
	Container Inspection Equipment Project	China		2020			47	47m grant	Equipment purchase
	The Project for Improvement of Port Vila Main Wharf	JICA	Port Vila	2008	2008	Completed	15	15m grant	Infrastructure construction

3.3 Results for subtask 6

The adoption of the 2023 IMO GHG Strategy aims, as a matter of urgency, to phase shipping GHG emissions out as soon as possible, while promoting, in the context of this Strategy, a just and equitable transition, that is to reach net zero GHG emissions by 2050. Given such, there is the need to investigate the mitigation of potential social, environmental and economic effects of the implementation of GHG reduction measures in the form of a fuel standard and a maritime GHG emissions pricing mechanism. By including both developed and developing States, the shift can ensure that no-one is left behind and that the most vulnerable communities and workers receive different kinds of support and assistance during this time. It is worth noting that States including LDCs and SIDS may bear a disproportionate amount of the financial burden linked to climate change mitigation efforts, as well as the consequences of climate change, therefore IMO called for particular attention to study the impact of GHG emission reduction measures on States (IMO, 2023). Thus, pathways (approaches) to mitigate, remedy and avoid the impact of this transition on States can be identified. In this subtask, these pathways are divided into addressing mitigation of the use of zero or near-zero GHG emission fuels and technologies through technological and economic measures. All of these pathways are applicable at national and international levels.

3.3.1. Pathways (approaches) to mitigate, remedy and avoid the impact of use of zero or near-zero GHG emission fuels and technologies

3.3.1.1 (Inter) national policies and regulatory frameworks

Nationally, governments have the key responsibility to introduce the policy frameworks needed to accelerate just transition and convene social dialogue (UNDP, 2022). Policies and regulations are the backstop for decarbonization (Alamoush et al., 2023). Such policies should align with the just transition principles ensuring that the shift to clean shipping technologies is fair, inclusive and benefits all stakeholders while also prioritizing social equity, labour market adjustments, job creation, improvements in job quality and incomes and community well-being (ILO, 2015; UNDP, 2022).

Policies and regulations that encourage the adoption of clean technologies and zero or near-zero GHG emission fuels in the shipping sector are required. In this regard, regulatory frameworks can accommodate emerging technologies and open the space to production and transport of zero or near-zero GHG emission fuels and technologies. For example, in Norway, the government's Green Shipping Programme supports the development of environmentally-friendly maritime technology, aiming for a just transition by creating jobs and fostering innovation (Alamoush et al., 2022).

Given the rapid pace of technological development, it is worth noting that policies can be designed to provide a supportive environment for innovation. Flexibility of regulations and policies is also important because it allows for adjustments based on new information and experiences.

Internationally, the UNCTAD *Review of Maritime Transport (2023)* emphasised the importance of national and international regulations in minimizing uncertainty and creating a level playing field to promote measures to lower the cost or price gap between alternative and conventional marine fuels (UNCTAD, 2023). Regulatory frameworks minimise uncertainty; such uncertainty prevents shipowners' timely investment in a new and modern fleet that runs on low or zero carbon fuels and also delays the introduction of onboard and onshore energy saving and green technologies (UNCTAD, 2023).

3.3.1.2 International collaboration and diplomacy

International cooperation through agreements and protocols to address global challenges associated with the adoption of new technologies in the shipping industry is important. This helps establishing and strengthening international frameworks that promote collaborations and establishing uniform regulatory and policy frameworks including, but not limited to, sharing of best practices, research findings and technological advancements. Governments can work together to harmonise regulations and agree on sharing best practices and promoting knowledge exchange. This includes founding forums for dialogue and cooperation to address common challenges and promote a unified approach to shipping decarbonization.

Collaborative efforts are deemed useful as this ensures a coordinated global response to the implementation of the IMO GHG Strategy (IMO, 2023). In addition, this promotes uniformity in the take-up of greener fuels and electrification, thereby reducing the risk of market distortions and ensuring a level playing field for all States. Similarly, limited variations in regulatory frameworks between countries keep away negative economic consequences.

3.3.1.3 International capacity-building and technology transfer

Capacity-building programmes and technology transfer initiatives should be facilitated to ensure that States have the knowledge and resources to adopt and manage new technologies effectively. Many developing countries may lack the expertise and infrastructure needed to adapt to the transition in the shipping sector. The same is true regarding the support to developing countries, particularly SIDS and LDCs, during the transition (UNCTAD, 2023). Voluntary technology transfer and capacity-building can bridge a technology gap, promoting a more inclusive and globally equitable implementation of the 2023 IMO GHG Strategy and benefiting from the transition to greener fuels.

Capacity-building can also help ensuring that States have the skills needed to operate new technologies. Technology transfer from developed countries to developing countries involves, among others, collaborative research initiatives, joint ventures or technology-sharing agreements. Courses and training programmes, potentially sponsored by developed countries, can be initiated to share knowledge and expertise in sustainable shipping practices with professionals from developing countries. It is worth noting that the Global Maritime Technology Cooperation Centres Network (GMN)[6] Network, supported by IMO, can play a role in offering capacity-building and be a medium that facilitates the transfer of maritime technology to developing countries.

3.3.1.4 Investments and Financing Mechanisms

According to the recent UNCTAD report (*Review of Maritime Transport*) (UNCTAD, 2023) that addressed shipping just transition, investments of additional $8 billion to $28 billion annually are required to decarbonize the fleet by 2050. However, fuel infrastructure investments are expected to exceed onboard investments. Scaling up fuel production, distribution and bunkering infrastructure to supply ships with 100% carbon neutral fuels by 2050 will likely require annual investments of around $28 billion to $90 billion. The report suggests that, according to some estimates, decarbonization could raise annual fuel costs by 70 to 100% compared to current levels (UNCTAD, 2023). These large cost projections will not be realizable through current funding strategies, while the higher shipping costs, as well as associated

6 Global maritime technology cooperation centre network officially launched (imo.org)

diminished global trade activity, could disproportionately affect LDCs and SIDS (UNCTAD, 2023). The significance of LDCs and SIDS is emphasized due to their sharp vulnerability to climate change impacts. Furthermore, these countries commonly count on maritime transport and trade as strategic drivers of their economic development. Without targeted actions and investment, these States could consequently encounter a double shock of climate change impacts (disruptions) in addition to the increasing shipping costs.

In support of such countries, international financial mechanisms, such as green bonds or dedicated funds subsidies, grants, incentives (including for first movers) or favourable financing terms (Smith et al., 2021; Abram et al., 2022; Alamoush et al., 2023), could also be used to provide financial support and incentives to boost emerging business opportunities arising from alternative fuel production, storage, bunkering and distribution (e.g. for building alternative fuel infrastructure and investment in renewable energy generation) while seizing business opportunities relating to the energy transition. Additionally, funds can target investment in climate change adaptation, trade and transport reforms, as well as transport and digital connectivity (Alamoush et al., 2021a; UNCTAD, 2023). The same is true by utilising revenues (funds generated) of the proposed IMO mid-term measures such as levies on bunker fuels or carbon tax (economic measures). There are also global funds that can be approached, such as the GCF, which supports projects globally that aim to address climate change, including investments in sustainable transportation infrastructure (Buchner et al., 2014).

At the national level, in the context of the IMO GHG Strategy, States should ensure a just and equitable transition in maritime transport by investing in people and places (e.g. maritime workers, seafarers, ports, etc.) and those investments may come from a combination of public and private capital (UNDP, 2022; Alamoush et al., 2023). States could facilitate the establishment of agreements with financial institutions so that ports, shipping companies and shipowners can access loans with differentiated interest rates for the development of low-emission infrastructure or for the deployment of green technologies on board ships. Private sector investment has a critical influence on both environmental and social outcomes by facilitating provision of capital and access to financial services in a broader sense (Smith et al., 2021; UNDP, 2022). Therefore, efforts can be exerted to engage the private sector by creating a favourable investment environment through regulatory certainty and financial incentives (International Energy Agency, 2021; Smith et al., 2021; UNDP, 2022).

3.3.1.5 Social, economic and environmental impact assessments

The 2023 IMO GHG Strategy, which calls for a shift to uptake zero or near-zero GHG emission technologies, fuels and/or energy sources in shipping, should be updated regularly, particularly embracing an assessment of its impacts on States. In particular, this should include developing countries as well as LDCs and SIDS, and their vulnerable economies which frequently encounter higher freight rates as they greatly depend on maritime transport for trade, consumption needs and economic development (UNCTAD, 2023). Such impact assessment may not only be conducted by international bodies but also at the national level by States (Abram et al., 2022). Impact assessments need to conduct qualitative and quantitative assessments (e.g. modelling) to show feasibilities and also approximate the impacts of shipping decarbonization measures on countries' key indicators such as GDP, employment, skills, income distribution and gender equality among other social, economic and environmental impacts. The following are key impacts that can be considered in assessments.

Social impact assessment

The energy transition in international shipping will definitely generate social impacts. Thus, it is necessary to conduct thorough assessments of the social impacts of decarbonization efforts on States and local communities, including any negative and/or positive impacts. This enables implementation of the right measures and mitigation plans to address any issues such as potential job displacement and ensure a just transition for workers affected by changes in the shipping industry (Just Transition Initiative, 2021; Abram et al., 2022).

Economic impact assessment

Similar to its social impact, it is expected that there will be economic consequences, emanating from the measures adopted in line with the IMO GHG Strategy, on States and local communities, such as increased cost of transport, job losses, increased costs of services and commodities and remoteness (Rojon et al., 2021). Continuous assessment therefore would be required. This is because assessments enable fair, just and equitable distribution of funds, benefits and financial support, in addition to developing targeted interventions and policies that mitigate negative economic consequences (Just Transition Initiative, 2021).

Environmental Impact Assessment

Nationally and internationally, in cooperation with governments, academia and public- and private-sector organizations, environmental Life Cycle Assessment (LCA) approaches need to continue the analyses of the upstream footprint of alternative fuel production in local and international contexts, including shipping GHG life cycle of the different fuels (well-to-wake), as well as fuel abatement potential and production limits such as the biofuels (UNCTAD, 2022; UNCTAD, 2023). The same is true regarding other environmental impacts, particularly air pollutants that have health consequences.

3.3.1.6 Research and development support

The pursuit of zero or near-zero GHG emission fuels that decarbonize the shipping industry is not an easy task as each source of fuel may have benefits and disadvantages, and restrictions including other obstacles that may unfold in the future. Therefore, efforts should continue to invest in research and development (R&D) of zero or near-zero GHG emission fuels (e.g. biofuels, hydrogen, ammonia) and energy-efficient technologies on board ships (UNCTAD, 2022). Countries should allocate resources for research and development and support innovations to enhance the efficiency and effectiveness of clean technologies (e.g. energy storage, fuel production, fuel-efficient engines, alternative and renewable energy and emission reduction technologies) and addressing technological gaps for the shipping sector. Overall, investment in R&D can accelerate the development of cost-effective and scalable technologies (Alamoush et al., 2023). In this sense, building partnerships between governments, academia and industry stakeholders helps nurturing knowledge-sharing and collaboration, while scaling up endeavours helps realising a sustainable and resilient shipping industry and making the transition more feasible for States (UNCTAD, 2023). Finally, the literature review indicated gaps in the literature on incentives such as patents and rewards for those researching, developing and deploying decarbonization technologies. Still such an approach may help in accelerating global shipping decarbonization.

3.3.1.7 Adaptive governance and new business models

With the advancement of technologies, States need to implement adaptive governance structures that align with changing circumstances, according to the literature (Okereke et al., 2009; Smith et al., 2021). In other words, adaptive governance allows maintaining flexibility and relevancy in regulatory frameworks, which can accommodate emerging technologies and facilitate timely adjustments in response to new information and experiences. As such, regulatory bodies can quickly adapt to new information and developments.

On the other hand, while the shipping industry mainly includes shipowners, operators and charterers, brokers, insurance providers; new business models by the financial sector can include an increased involvement of technology manufacturers, fuel and energy providers as they play a key role in the transition (Alamoush et al., 2023). This can be called a joint business model where all partners have a role to play, and they all share costs and risks. An example is the shoreside electricity and charging stations at ports. Other business models include ESC, or MEC, that is to guarantee energy supply which enables a swift transition to zero or near-zero GHG emission fuels. In other words, ports as bunkering hubs need to include new business models other than typical ones that involve the port authority or terminal operators by encompassing fuel and energy providers and producers, bunkering companies and even shipping lines and owners that can get into port business by developing bunkering infrastructure and providing the required zero or near-zero GHG emission fuels in a timely manner. On this basis, all the transition costs (finance) and revenues are shared among them and even, to a certain extent, operations are also split with some other onshore entities.

3.3.1.8 Monitoring and management

Continued monitoring for complex dynamics is a key to inform effective climate actions (Naeem et al., 2023). Monitoring generates data that assess economic and environmental implications and implementation of shipping decarbonization. Data guide the decision making, enlighten regulatory efforts, and support management of sustainable, fair and transparent shipping decarbonization practices.

Monitoring can be categorized as follows:

- **Environmental monitoring**

It is apparent that there is no silver bullet measure that will decarbonize industries; shipping is no exception. There will be combinations of different fuels and technologies (DNV, 2019a, 2019b; Maersk Mc-Kinney, 2021). While most of the environmental impacts were presented theoretically, there might be variations in them. Therefore, robust monitoring and reporting mechanisms to track the environmental impacts of shipping decarbonization pathways by international and national bodies should continue.

This allows for evidence-based decision-making and informs policy adjustments, and may also identify areas that require additional support. Additionally, monitoring allows developing strategies that intend to manage and mitigate unintended consequences, and potential environmental risks, ultimately ensuring that interventions are effective and aligned with the intended goals (IMO, 2020).

- **Costs monitoring (freight rate surcharges)**

It is worth noting that the current formulas utilised to determine freight rates and surcharges, together with fuel surcharges, are still debatable by shippers who require a more transparent approach (UNCTAD, 2023). Therefore, taking future fuels into consideration, monitoring the advancement of freight rates and costs of the shipping decarbonization and energy transition is significant.

Considering the current acceleration toward adoption of new zero or near-zero GHG emission fuels in shipping, a thorough reflection of pricing and charging mechanisms for zero or near-zero GHG emission fuels is required. This is because this will influence the cost borne by carriers, shippers and traders (UNCTAD, 2023). There is a need for transparency in showing how freight rates and new zero or near-zero bunker fuel prices will be determined and incorporated into final costs. Thus, UNCTAD called for an advisory mechanism that guides the setting of freight rates and fuel surcharges which guarantees transparent, fair and sustainable freight rate and surcharge price-setting practices, eventually leading to a smooth decarbonization process (UNCTAD, 2023). According to UNCTAD, the advisory mechanism (by an international organisation such as IMO or UNCTAD, for example), can include shipping, trade and relevant stakeholders in the maritime supply chain, including government and regulatory bodies.

- **Implementation monitoring**

Regardless of the decarbonization technology or economic measures adopted, implementation may differ from region to region, even in different shipping routes (i.e. there may be some exemptions in some areas and routes or differing bunkering fuels). Thus, there is risk of carbon leakage and excessive tax base erosion (UNCTAD, 2023). Ships may alter their routes to escape the system and/or refuel outside routes' or regions' jurisdiction, leading to changes and relocations in transhipment and bunkering hubs (Lagouvardou and Psaraftis, 2022). Another issue that may arise is the quality of fuels used by ships and bunkering stations which may not have the claimed abatement potential or life cycle emissions. Monitoring of implementation by States minimises such risks that undermine the implementation goal.

- **Trends monitoring**

Different shipping trends need to be monitored to help in decision-making and boosting streamlined implementation. First, there is a need to keep monitoring the volume of zero and near-zero fuels and energy sources that will be needed at different points in time, through technical measures such as a fuel standard in order to create certainty about fuel volumes (UNCTAD, 2023). Second, trends of ship financing for fleet renewal and green investment also need to be monitored in order to scale up ship financing and investment levels and have transparency (Smith et al., 2021; UNCTAD, 2023). Third, considering the dilemma of a slow growing fleet, i.e. ageing ships, monitoring trends in shipbuilding capacity is thus important to ensure a timely energy transition for shipping decarbonization (UNCTAD, 2023). This is vital because reaching the 2023 IMO GHG Strategy goal requires about 80million gross tonnes of zero-emissions vessels which need to be handled by shipyards – both as newbuilds and retrofits – each year between 2027 and 2040 (Splash, 2023). This is beyond the current capacity of shipyards, thus, there is an urgent need for shipyard expansion to meet global demands for decarbonization (UNCTAD, 2023).

3.3.1.9 Public and stakeholder engagement

Engagement of the public and stakeholders in the decision-making process, particularly when formulating and implementing policies, is a vital step forward that ensures that their concerns and perspectives are considered. Since shipping cannot decarbonize on its own, the decarbonising endeavours can bring together different stakeholders from various sectors, including the industry and its leaders, carriers, ports, manufacturers, shippers, investors, energy producers and distributors, citizens, policymakers, regulators, labour unions, environmental organizations and local communities. This improves the decision-making processes and ensures that diverse perspectives are considered when formulating and implementing policies (Reed, 2008). This kind of engagement fosters a sense of ownership and cooperation, facilitating smoother transitions (Huttunen et al., 2022).

Nationally, inclusive decision-making enhances the legitimacy of shipping decarbonization policies, balances economic and environmental concerns and helps identify potential challenges and solutions that might not be apparent through a narrow lens. A case in point, the Danish Maritime Forum brings together stakeholders from the shipping industry, government, and civil society to discuss and shape policies for sustainable shipping. In the same regard, for streamlined transition, OECD suggests the formation of industry-NGO partnerships, industry-industry partnerships as well as government-industry partnerships (OECD, 2004). Establishment of alliances and coalitions among stakeholders, e.g. between government, business and academia, to finance and carry out research to improve the efficiency or to participate in decision-making, are important steps to the transition (Smith et al., 2021). Of consideration, while incentives and open dialogues attract stakeholders, voluntary agreements can also be utilised to motivate stakeholders to act beyond regulatory requirement (Alamoush et al., 2021b; Tzeiranaki et al., 2023). The following subsection presents the green shipping corridors as a voluntary cooperation initiative that encourages stakeholders' engagement to contribute to shipping decarbonization.

***Green shipping corridors*:**

The COP26 Clydebank Declaration declared a commitment to support the establishment of green shipping corridors and thus sought to leverage collaboration among various stakeholders. Green shipping corridors are routes that leverage collaboration across multiple stakeholders operating between two or more ports (Button et al., 2022). The goal of the corridors is to offer bunkering options for ships running on zero or near-zero GHG emission fuels, test various solutions and support first movers in their efforts (UNCTAD, 023; GHC, 2023). Taking into consideration the collaborative approach in the corridors, and variations in regions' implementation and capacities, there is a need for stakeholders' engagement at the national and international level to address challenges and opportunities and move forward (Smith et al., 2021). In this sense, it is still vital to make sure inclusiveness of green shipping corridors that not only include developed countries but also benefit developing countries, particularly SIDS and LDCs (UNCTAD, 2023). It is worth noting that some developing countries engaged in the green shipping corridors by signing MoUs, such as Chilean green corridor network, Australia-East Asia iron ore green corridor, QUAD Shipping Taskforce green shipping corridors (USA, Japan, Australia, and India), US- Fiji- Panama Green Corridor and South Africa- Europe Iron Ore Corridor (Ismail, 2023). While port authorities are very important stakeholders, carriers, terminal operators, manufacturers, shippers, investors, energy providers, producers and distributors are also important to lead the crucial changes. While ports started positioning themselves in a wider environmental ecosystem, such as engagement in shipping decarbonization (Alamoush et al., 2021b, 2022), they should align their activities with global policy decarbonization processes and ensure sufficient supply of zero and near-zero GHG emission fuels and infrastructure for distribution (Alamoush et al., 2023; UNCTAD, 2023).

3.3.1.10 Awareness and public acceptance improvement

Improving awareness of public and their acceptance of the transition is of utmost importance and crucial for successful implementation. It minimises future managerial inertia (a barrier to decarbonization) (Alamoush et al., 2023). This involves improving awareness of ports, energy providers and technology manufacturers, with respect to the maritime decarbonization needs (fuels, technologies and other measures) and decarbonization implementation pathways and how they can contribute to the progression of decarbonization efforts. The same is true regarding raising the awareness of the public about the benefits of decarbonisation and the importance of transitioning to cleaner shipping practices, including highlighting the consequences of decarbonization measures implementation in terms of economic and social impacts while stressing that this is done for a worthy cause (climate change mitigation) (Alamoush et al., 2023, 2021b). Understanding how the public perceives different zero or near-zero GHG emission fuels minimises future conflicts with local communities and other organizations. For instance, a study in the UK found that biofuels and hydrogen are favoured due to their perceived low risk and lack of negative by-products while ammonia is disliked due to its safety risks (Carlisle et al., 2023). Improving the public acceptance encourages public support for government initiatives and fosters a sense of shared responsibility for sustainable shipping practices.

Informed and engaged citizens contribute to a smoother transition and more successful implementation of GHG reduction policies (Alamoush et al., 2023).

3.3.1.11 Infrastructure Improvement

The shift to a decarbonized shipping sector needs infrastructure considering that lack of infrastructure can be a barrier to the adoption of greener fuels and electrification (Alamoush et al., 2023). Building port bunkering infrastructure (alternative fuel production, distribution, and supply) and energy transition technologies (i.e. renewable energy generation, onshore power supply, grid upgrades and smart recharging stations) accommodate clean energy technologies and facilitate the viability of sustainable shipping decarbonization practices. While States can seek investments and funds to improve their infrastructure, national efforts need to continue, if possible, to accommodate shipping decarbonization infrastructural needs.

The role of ports infrastructure for shipping decarbonization should not be neglected, importantly the bunkering and electric supply infrastructure, for instance the integration with the green shipping corridors (Alamoush et al., 2022). As a response to the European Green Deal, the Port of Rotterdam is investing in infrastructure for shore power and hydrogen refuelling stations to promote shipping decarbonization (Button et al., 2022). The following subsection focuses on port and shipping reforms other than zero or near-zero GHG emission fuels and technologies.

***Port and shipping reforms*:**

Ports and ships should focus on other areas beyond the zero or near-zero GHG emission fuels and energy transition technology by adapting efficient technologies that facilitate shipping trades, transactions and operational efficiency (UNCTAD, 2023). This includes swifter adoption of digital technologies (digitalization such as electronic data interchange, single window, port community systems and electronic bills of lading) and incorporation of Artificial Intelligence (AI), blockchains, digital twining, machine learning, Internet of Things (IoT), including simplifications of customs processes at ports and ship performance optimization platforms (e.g. monitoring, routing, speed, predictive maintenance, crew training) (Ölçer et al., 2023). Such technological reforms strengthen port performance and resilience, reduce ships costly delays and help accelerate decarbonization by increasing the efficiency and sustainability of shipping operations and port processing procedures (UNCTAD, 2023). While this ultimately reduces the rising cost of trade owing to GHG measures in general, ports and governments should encourage public–private collaboration to achieve such reforms. It is worth noting that a balance should be undertaken between incorporating AI, blockchain, etc., and national security and data issues.

3.3.1.12 Labour skilling and safety measures

The transition in shipping decarbonization will have implications on maritime workers skills, in ports, ships and even in shipyards. Therefore, there is a need to implement skill development and training programmes to equip the workforce with the necessary skills for the emerging clean energy in shipping sectors. This improves the operation of new technologies and fuels, leads to smother transition and minimizes the risk of job losses or displacement. Maritime educational training (MET) programmes can include courses that reskill current ships and port workers with skills and competencies to handle and operate zero or near-zero GHG emission fuels and maintain engines while focusing on improvement in safety measures. The same is true regarding the future students by enabling them to meet the evolving maritime industry demands. In fact, there can be safety guidelines on handling and operation of all the zero or near-zero GHG emission fuels. Such guidelines can be generated at the international level (e.g. by classification societies (Smith et al., 2021)), potentially in collaboration with international partners or even at national level if the former is non existent or unachievable. It helps that the adoption of new fuels and other technologies does not compromise safety standards. It is worth noting that IMO sets global standards for the safety of shipping, including guidelines for the use of some zero or near-zero GHG emission fuels.

Overall, lack of training and skills and the safety issues are considered barriers to decarbonization (Alamoush et al., 2023). Hence, ship crews should be adequately trained in the use of zero or near-zero GHG emission fuels and related energy transition systems (UNCTAD, 2023). The same is true regarding port and shipyard labour considering that a large number of new ships will be ordered and/or old ones refitted with new technologies, thus this facilitates and reduces the transition time.

3.3.1.13 Economic diversification strategies

Maritime transport creates thousands of jobs directly and large number of other indirect (associated) jobs. The shift to zero and near zero GHG emission fuels including the implementation of a carbon pricing mechanism, influences countries' maritime trade, particularly States that highly depend on it as an economic driver and jobs. Some jobs could be lost due to shifts of trade to other hubs (because of economic measures) and low profits for ocean carriers that lead to keeping such countries remote and thus minimising their maritime related economic activities. Additionally, some old jobs that were dependent on fossil fuels activities will be phased out. Overall, decarbonization may result in distributional consequences in the form of job losses that may occur in certain sectors and/or communities, principally where dependence on fossil fuels or carbon-intensive practices are high (UNCTAD, 2023).

Therefore, international and national efforts can support the development of diversified economies in regions heavily dependent on traditional shipping-related activities, ensuring resilience to economic changes. This may involve economic incentives, investment in new industries, and support for entrepreneurships (Meadowcroft, 2009). For example, Iceland initiated economic diversification activities that include investments in renewable energy and sustainable fisheries, thus mitigating dependence on traditional shipping-related activities. Another example, the Scottish Government's support for offshore wind projects includes community benefit schemes, ensuring that local communities share the economic benefits of renewable energy development. On the other hand, while there are negative effects, there may be benefits emerging from the transition, hence, equitable distribution of benefits can be maintained to create new job opportunities and economic growth across different regions and communities. IRENA conducted the first-ever global estimate of large hydropower employment, showing approximately 1.5 million direct jobs in the sector (IRENA & ILO, 2022). Within this context, countries can incorporate gender and other equity considerations into transition policies to avoid exacerbating existing inequalities (Rainard et al., 2023). On the other hand, ILO also highlighted various opportunities concerning sustainable development, decent work and green jobs, putting forward a policy framework for a just transition (ILO, 2015).

3.3.1.14 Phased-in implementation

"Phased-in implementation" suggests gradual or incremental introduction of a system, policy, regulation, technology, or any change over a particular period. This approach allows for a smoother transition, minimizes disruptions and often provides stakeholders with the opportunity to adapt to the new conditions. The phased-in implementation strategy is frequently used in several fields, including technology, business processes and regulatory frameworks (Trencher et al., 2022). Considering that implementation of the maritime transport decarbonization measures (technologies and economic measures) will have impact on different States, particularly least developed and island States, it can be said that phased in implementation can be considered for States and ships calling in at these States or even regions. This allows ships and States to gradually transition without facing sudden and disruptive changes while at the same time giving shipowners and operators time to gradually retrofit ships over several years without undue economic strain. This can be particularly beneficial for States with resource constraints as it allows for tailoring transition timelines and milestones to their unique circumstances considering the economic conditions, infrastructure readiness and technological capacity.

3.3.1.15 Exemptions

Not all States would be able to adapt to shipping transition and there will be various impacts on these States' maritime transport; this includes transport costs increase, geographical remoteness, loss of some types of cargo and issues in disaster response, among others. Therefore, it is vital to introduce an international legal framework that allows for exemptions or special consideration for ships calling at certain States or regions taking into account their economic conditions, developmental status or the specific challenges they face, even any changing circumstances due to the transition. This ensures fair and accountable implementation and is aligned with the principles of environmental sustainability. It is also deemed necessary to have transparent and accessible processes for States to request and obtain legal exemptions. Of consideration, the work of (Dominioni, 2023) identified benefits and drawbacks related to exemptions and the strategic use of carbon revenues. The author also revealed that, while caution is required because of some drawbacks, exemptions have some potential merit in addressing equity considerations.

Nexus between the proposed pathways and IMO criteria for the impacts on States:

In the initial strategy 2018, IMO called for considering various criteria to study the impact of (a) measure(s) as appropriate using the different approaches (see table 22, left column). The previous section provided various pathways that could minimise any arising issues in relation to the criteria terms. Table 23 (right column) also exhibits how each proposed pathway may address such issues.

*Table 23. Linking the issues that impact states (IMO criteria) and the proposed pathways of mitigation**

Impacts (IMO criteria)	**The pathways that mitigate such impacts ***
1. Geographic remoteness of and connectivity to main markets	Develop strategies to improve connectivity, such as investing in efficient transportation, bunker, and port infrastructure and setting up transport corridors to decrease the impact of remoteness (11,12). This could encompass international collaboration to enhance maritime connectivity (1, 9).
2. Cargo value and type	Implement measures to ensure that the transition to alternative fuels does not disproportionately affect the transportation of certain types of cargo. This might involve targeted incentives (4,7,13), exemptions (15), or phased implementation (14) for critical or high-value cargoes.
3. Transport dependency	Differentiate transportation modes and economic activities and invest in alternative transportation infrastructure (e.g. rail or road networks) to reduce absolute dependency on maritime transport (1, 3, 13). This can enhance resilience and reduce vulnerability to disruptions caused by the transition to alternative fuels.
4.Ttransport costs	Investigate cost-sharing mechanisms, subsidies, or incentives, capacity building, research and development (3, 4, 6, 7) to offset potential increases in transport costs. This could include financial support (4) for States during the transition period or the development of cost-effective technologies.
5. Food security	Purpose policies that prioritize the transportation of food-related cargo, ensuring that the transition to alternative fuels does not compromise food security (14). Consider exemptions or support mechanisms for indispensable food shipments (15).
6. disaster response	Strengthen disaster response capabilities and coordination to address potential disruptions caused by the transition (2,3). This may involve creating contingency plans, stockpiling essential

	goods and enhancing communication and coordination among relevant stakeholders (9).
7. cost-effectiveness	Develop and promote alternative fuel technologies that are cost-effective and feasible for states with varying economic conditions (2, 4, 6, 8, 9). Encourage research and development to improve the affordability of alternative fuels (6). Monitoring of costs is very important to retain non-justified surcharges (8).
8. Socio-economic progress and development	Align the transition to alternative fuels with broader socio-economic development goals (5, 12). Invest in capacity-building programs (3), technology transfer, and collaborative initiatives that contribute to sustainable development and progress (9, 10).

** Numbers in the second column refer to the proposed pathways in the previous section.*

3.3.1.16 Summary

This section provided potential approaches to mitigate the impact on States from the implementation of candidate mid-term GHG reduction measures in the IMO GHG Strategy, which involves a shift to greener fuels and electrification in the shipping industry. It is worth noting that the literature that specifically addresses this topic is scarce and any abstract and citation database search using various combinations of mitigating the impact yields no results. Therefore, it was necessary to broaden the scope of this research by observing how the impacts of a transition using different fuels and technologies could be mitigated as the catalyst for building various pathways. Overall, it was found that the suggested mitigation approaches require a comprehensive and coordinated effort which, when integrated into the policymaking process, can contribute to a more just and equitable transition to a decarbonized shipping industry. By incorporating these approaches by international and national bodies, countries can mitigate the transition consequences and thus navigate the challenges and opportunities associated with decarbonizing the shipping industry while promoting a just and equitable transition.

3.3.2 Mitigating approaches in response to economic impacts

3.3.2.1 Step-based increase of the carbon price (in case of a levy)

In light of increased transportation costs and its impact on States, including SIDs and LDCs, proposals recommending very high levies may have difficulty achieving political feasibility. The impact assessment conducted by ICS and Clarksons Research suggests that "for some trades and cargoes, the initial application of a levy much in excess of $100 per tonne of CO_2 emitted might be more likely to be viewed by some Member States as being disproportionately negative" (IMO, 2022). This is in line with the ICS IMSF&R proposal (IMO, 2023c), which recommends $12.5 per tonne of CO_2. Similarly, a step-based increase of the carbon price could be an appropriate approach (Parry et al., 2018), that has been taken in Japan (2021), the Marshall Islands and Solomon Islands (2021) and ICS and Intercargo (2021) proposals. However, the motivation behind these proposals is not their design, but rather their perception of political feasibility (OECD/ITF, 2022). Despite this, we can also consider how high motivation can be maintained even at low tax rates. In the next paragraph, some approaches are discussed.

3.3.2.2 Boosting motivational effects of the carbon pricing mechanism in lower carbon prices

In three ways, the motivational force of a carbon pricing mechanism such as a carbon or fuel tax could be uplifted: increased transparency, creation of a rebate mechanism and differentiated tax mechanism based on ships' efficiency level.

Highest ships' emission transparency

A carbon pricing mechanism can drive shipowners in two ways: first, via *economic incentives* due to carbon tax payment, and second, via *market incentives* as a result of the transparency and visibility of ship energy performance to stakeholders (Svensson & Andersson, 2012). The low tax rates cannot compel shipowners to invest in green technologies. At an inflection point, the tax rate would be high enough to compel shipowners investing in green fuels and technologies rather than pay high taxes. Nevertheless, a very high tax rate is necessary to reach this inflection point. In the context of global trade, high tax rates can impose a trade cap and, therefore, be met with strong opposition from stakeholders. It is here that transparency and market incentives can play a crucial role in reducing the tax level with the same incentivising effect.

A carbon pricing mechanism with the highest degree of transparency forces ship operators to rethink their social and environmental image which is monitored by charterers, financiers and society. A high level of transparency, therefore, can create market incentives. The market incentives refer to the competitive advantage a green ship or shipping company has in the charter market, where charterers are looking for energy-efficient vessels (Svensson & Andersson, 2012). Coupled with economic incentives, market incentives can facilitate the adoption of energy efficiency measures and zero or near-zero GHG emission fuels by shipowners.

According to Masodzadeh et al., 2024a, increasing transparency and market incentives could reduce the need for significant economic drivers created by high tax rates which will allow for a carbon pricing mechanism to be implemented at a lower tax rate. This will reduce the impact of carbon pricing implementation on transportation costs and global trade. The desired level of transparency could be achieved through a transparent data collection and energy-rating system as well as revising IMO's Carbon Intensity Index (CII) formula by replacing the actual cargo tonnage instead of dead weight (Masodzadeh et al., 2024a).

A rebate mechanism at ports

Rebates could generally boost the motivational effect of the carbon pricing mechanism which would enhance its decarbonization impact (Muresianu, 2021). According to Pomerleau and Asen (2019) 'rebates make the tax code significantly more progressive'. A successful experience of rebate mechanism could be the NO_x Fund in Norway (BHP/BW/DNB/DNV GL, 2019). A recommendation could be a rebate mechanism at ports in the form of a global port incentive program (PIP) focused solely on CO_2 reduction. More explanation about the rebate mechanism at ports is provided in the next section.

Differentiated carbon levy

Masodzadeh et al. (2022a) argue that in fixed levy proposals, all vessels pay a fixed amount of tax per tonne of bunker fuel regardless of their level of energy efficiency. Alternatively, a differentiated levy would set the tax for each vessel based on its level of efficiency. Despite the easier implementation of a fixed levy, the effect of a differentiated levy is significantly greater in terms of decarbonization. Due to the fact that the fixed levy does not provide transparency based on the energy efficiency of the vessels, the tax amount may inevitably be very high for the decarbonization to be effective. The high level of tax creates a negative mindset in society. By contrast, a differentiated levy, with a much lower tax rate but with high transparency, can stimulate vessels to be more efficient in order to benefit from economic incentives (less tax payment), and market incentives (more utilization by charterers), and to be supported by financiers (Masodzadeh et al., 2022a).

3.3.2.3 Sustainable business models

In general, sustainable business models (SBMs) are tools through which stakeholders' interactions could be defined, revised and managed in a sustainable way (Fobbe and Hilletofth, 2021). From a management perspective, it is important to understand the multiple levels of stakeholder interactions in SBMs and their multifaceted roles within each level. By using SBMs, organisers can balance stakeholder needs, fulfil preconditions and set up interaction practices to generate sustainable value (Fobbe and Hilletofth, 2021). Various business models are available, for instance in supply chain integration (e.g. energy supply chain), including contracts, partnerships, alliances, joint ventures and ownership (Monios and Bergqvist, 2015). Business models can mitigate the economic impacts associated with the implementation of a carbon pricing mechanism by facilitating the energy transition through a proper definition of stakeholders' interaction. Various business models applicable to the shipping energy transition are briefly discussed in this section.

Joint venture

Joint ventures could be domestic or international. According to Nippa and Reuer (2019), international joint ventures could be defined as a subset of international strategic alliances. As well, they argue that international joint ventures are a form of corporate cooperation in which two or more independent organizations establish and maintain a separate legal organization in order to collaborate for mutual strategic interests and based on equity arrangements. By focusing on the strategic aspect of collaboration, the joint venture is viewed as a long-term strategic business model rather than merely a cost-saving initiative (Monios and Bergqvist, 2015). In order to form a joint venture, partners may undertake additional steps, including investing significant sums in equipment, signing contracts with other organizations, providing financial guarantees and taking risks in relation to the other partners (Monios and Bergqvist, 2015). Among the examples of joint ventures related to ports are the joint-venture terminals that are the result of close cooperation between port terminal operators and shipping lines (Wang and Meng, 2019). Co-investment of shipping companies in alternative fuel carriers such as ammonia carriers could be another example of a joint venture business model (Lloyd's List, 2023).

Investment in and operation of port infrastructures by shippers and shipping companies

The shipping companies in this model invest their technical expertise and capacity in the development and even operation of port infrastructure that is more in line with the equipment on board their vessels. This model allows shippers (cargo owners) to provide financial support as well (BASREC, 2014; ESPO, 2012; Saeed et al., 2018). Currently, investment in an onshore power supply mechanism at ports is the most common practice in this model. It is possible to expand this business model to other technologies and zero or near-zero GHG emission fuels. For instance, shipping companies whose vessels have switched to green fuels can invest in the production and supply chain of such fuels as well as bunkering stations at ports.

Maritime Energy Contracting (MEC) model

The MEC model is the result of close cooperation between technology providers and shipowners. The MEC model, by utilizing "savings as a service" approach (Halim et al., 2018), has been practised in the installation of scrubbers (Olaniyi et al., 2017; Olaniyi et al., 2018) and LNG retrofit (Olaniyi and Gerlitz, 2019) on ships. The model proposes renting technology from energy-saving companies (ESCOs) and paying for it entirely through fuel savings (Rehmatulla et al., 2017a). In this direction, Stulgis et al. (2014) have discussed two Third-Party-Finance models: Self-Financing Fuel-Saving Mechanism (SFFSM) and Emission Compliance Service Agreement (ECSA). The SFFSM model involves ESCOs investing in energy efficiency technology and recouping their investment through fuel cost savings. By applying the ECSA model, ESCOs assist shipowners with complying with new regulations (e.g. sulphur cap), such as by investing in dual-fuel LNG engine conversions and earning revenue from the price differential between low-sulphur fuels and natural gas. As another recommendation consistent with the MEC model, ESCOs investing in ship energy efficiency technologies may also invest in the relevant technologies at ports to close the loop. As a result, shipowners can rest assured that new technologies installed on board are compatible with port equipment, and, in addition, port management can maintain loyal customers for their energy efficiency investments.

Energy Supply Contracting (ESC) model

In the shipping industry, the ESC model represents a new emerging economic model. In this model, energy is provided at the consumption point by energy providers (producers and transporters) to clients who are economically less powerful and have no motivation to invest in such a distribution network. Providing liquid biogas (LBG) to seaports may constitute an example of this model. The success of this model depends, of course, on subsidies provided to biofuels such as LBG (Philipp, 2020).

Long term charter parties

An important factor contributing to conflicts of interests (split incentives) in energy efficiency investments is the inconsistency between shipowners and charterers regarding who can invest in energy efficiency and who could benefit from it. This happens more often in time charter parties. In general, charter parties and charter rates do not reflect the energy efficiency status of vessels. In this regard, longer contracts, covering at least the payback period of new technologies installed, may encourage shipowners to adopt these technologies. As part of the ordering process for new ships, a long-term charter contract may be negotiated based on the adoption of energy efficiency measures, such as the use of gas-powered engines (ITF/OECD, 2018; Halim et al., 2018; Rehmatulla and Smith, 2020).

Book and Claim model

According to Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (2023), the 'Book and Claim' process can play a significant role in speeding up the early phases of shipping's decarbonization. Through this model, alternative fuel adoption can be advanced at an early stage, even when fuels and vessels are not readily available. As a result of Book and Claim, shipowners and fuel providers can build up a business model for shipping decarbonization by developing early demand from shippers, even when there is no established fuel pathway. The implementation of a 'Book and Claim' system in the maritime industry can enable decoupling of GHG emissions from transport activities, thereby increasing willingness to pay and, as a consequence, encouraging green shipping activities. While zero or near-zero GHG emission fuels are consumed on ships, their emissions are not directly related to the transportation service. In addition, investors who are not physically connected to the shipping industry may be able to purchase these lower emissions and claim their benefits in the future. By implementation of the Book and Claim model, the gap between supply and demand for zero or near-zero GHG emission fuels could be bridged; as a result, zero or near-zero GHG emission fuels are consumed where there is a supply and their benefits and costs are dedicated to those areas where there is a demand. A 'Book and Claim' strategy is similar to the way in which green electricity certificates are sold and purchased today. By purchasing green electricity certificates, we ensure the grid will receive power from renewable sources, but the green portion of electricity may not be physically delivered to our residence or workplace. While customers do not directly consume renewable electricity, they can still benefit from lower emissions by paying for and claiming them. Purchasing and selling green shipping via Book and Claim follows the same logic (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2023).

3.3.2.4 Effect of free riders

By overlooking the role of "free riders'', the public image of energy policies can be negatively affected. Free riders are vessels that are exempt from regulations (Nikolakaki, 2013) for reasons such as their gross tonnage or their function. A large proportion of the EU ferry fleet (around 50%) is not covered by the EEDI (under 400GT), and around 80% is not covered by the EU MRV (under 5,000GT) (Rehmatulla et al., 2017b). Likewise, 6% of total shipping emissions are attributed to service and offshore vessels subject to national regulation (Lützen et al., 2017). As a result, the exclusion criteria within the regulatory scope (ship type, ship function and ship size threshold) are crucial.

It can be noted that smaller ships that fall into this category, which usually operate in coastal or short-sea shipping, are the easiest to abate in comparison with larger ocean-going ships. Some examples of this segment include fishing vessels, harbour craft, yachts, OSV, ferries and service vessels. It is possible to completely electrify new builds in this segment or to switch to green fuels since they do not require a large fuel storage capacity. By exempting this segment of shipping from global taxation, a significant amount of carbon reduction potential can be lost. It has been estimated that the annual emissions of ships exempted from EU MRV regulations (under 5,000GT) are almost the same as the annual emissions of Denmark, according to T&E (2022). It is possible that exempting a major segment of shipping from tax regime will shift the economic burden of decarbonization onto other segments which is in conflict with the principle of equitable energy transition. On the other hand, it can also be noted that the majority of domestic fleets in SIDS and LDCs fall within this segment that requires particular attention during the policy formulation process.

3.3.2.5 Stakeholders' analysis

According to the revised assessment procedures (IMO, 2023a), both global modelling and complementary stakeholders' analysis may be included in the assessment of impacts on States, especially when the assessed State is a small-scale economy with a low degree of connectivity, in order to account for imports of essential goods, food security and disaster response. The precise analysis of stakeholders is a prerequisite and a cornerstone of many other activities in the process of formulating and implementing a carbon pricing mechanism. According to Osterwalder and Pigneur (2010), identification of stakeholders, their interests and expectations, their potential, resources and abilities, and their current interaction with other partners can prepare the scene for proper designing of communication channels, business models and standard connections between them. As the maritime energy transition is strongly tied with land-based industries in terms of green energy and zero and near-zero GHG emission fuels production, it is crucial that special care be paid to identify and analyse the land-based stakeholders and investigate about a well-designed energy supply chain and its actors from well-to-wake. This will result in a win-win deal for all actors in the maritime and non-maritime sectors to exploit their potential in this transition. It is possible to identify relevant stakeholders on a local, national, regional or global scale (IMO, 2023a). An example of the benefits of a detailed stakeholder analysis would be the ability to gain an overall perspective on how the carbon revenue can be spent.

3.3.2.6 National dataset

According to OECD (2023), lack of information is one of the major barriers to equitable energy transition, in particular in the case of SIDS and LDCs. OECD (2023) argues that "more robust climate data and services are essential inputs for policies aimed at preventing climate-related hazards, attracting investment, and accessing international climate finance". The use of local data from SIDS is required for project design and monitoring (OECD, 2023). Some argue that it would be crucial when developing a framework and set of criteria for revenue distribution to incorporate precise data from different maritime stakeholders as well as national actors outside the maritime sector. Data from these sources could be collected to form a national dataset for each country. There has been a data shortage regarding some countries, according to the World Bank (2023), when it comes to determining who is eligible to receive carbon revenue to support investments in production and distribution of zero or near-zero GHG emission fuels. OECD (2023) argues that SIDS may lose many opportunities due to technical knowledge constraints and limited capacity to engage in climate negotiations (for example, modalities for dedicated funds or facilities), where funding priorities are discussed and agreed upon. A lack of data has likely prevented many countries from identifying potential investment opportunities. SIDS and LDCs may be able to showcase their potential in energy transition through a unified and standard format for national datasets (OECD, 2023). This approach allows them to demonstrate their successful experiences from previous projects and propose their future plan and roadmap. According to the revised assessment procedure (IMO, 2023a), Member States and stakeholders can be encouraged to share detailed data as well as submit relevant illustrative case studies representative of broader trade conditions in order to facilitate a quantitative and qualitative analysis of impacts on certain sectors/commodities, particularly in regions where data are lacking.

3.3.2.7 Supporting small shipping companies

According to Masodzadeh et al. (2022a), small shipping companies could be very vulnerable in energy transition. In many cases, low-level investors, with their maximum capital, attempt to purchase a (few) ship(s) and enter the shipping business without the economic resilience to improve their operational safety and efficiency. This type of business strategy, however, often leads to financial and operational risks, lack of access to finance and capital, lack of economies of scale and difficulty in competing with larger companies. The transaction costs for such small companies are very high considering the very low number of vessels (Jafarzadeh and Utne, 2014; Faber et al., 2009). Given the fact that financing the energy efficiency projects are limited to fleet-scale retrofits, smaller shipowners have serious challenges accessing bank debt for their retrofit projects (Faber et al., 2011; Johnson et al., 2014). A review of ship ownership study in 2012 shows that companies in the dry bulk sector own just over four ships and in the oil tanker sector under three on average. Because of the low economies of scale associated with this low average ownership, technology providers are reluctant to cooperate with small shipping companies and banks are unable to finance these initiatives (Rehmatulla et al., 2017a).

In response to this problem, Masodzadeh et al. (2022a) argue that governments, by identifying small shipping companies and by offering incentive packages, can encourage them to merge to establish a larger enterprise with higher risk-taking power and a resilient economy and being beneficiary of economies of scale. By this approach, they will have a strong organizational structure to manage the safety and environmental issues. While the IMO's Multi-donor GHG Trust Fund (GHG TC-Trust Fund) may be able to provide financial support for technical cooperation and capacity-building activities to implement the 2023 IMO GHG Strategy, other funds possibly including a potential IMO fund that manages the collection revenue from a global maritime GHG emissions pricing mechanism, may be able to provide support for such incentive packages (Masodzadeh et al., 2022a).

3.3.2.8 A well-designed carbon revenue distribution network

Literature suggests that an appropriate organizational structure can assist policymakers in making the best use of carbon revenues. The World Bank (2019) argues that it is possible to enact these arrangements by establishing appropriate legal and administrative frameworks, procedures for managing revenue flows, effective stakeholder engagement and accountability procedures. The involvement of stakeholder groups as well as monitoring and reporting procedures will help to increase public acceptance of carbon pricing which is key to its long-term success (World Bank, 2019). According to Pomerleau and Asen (2019) "the economic effects of a carbon tax vary significantly depending on how the generated tax revenues are used".

According to the World Bank (2019), it is important to have clear legal and administrative frameworks in place to ensure that carbon revenues are properly targeted and that administrative costs are kept to a minimum. When there are already existing structures for allocating revenue, administrative arrangements can be relatively straightforward; however, when there are not, this may require the creation of new bodies to govern the use of revenue for specific programmes. Moreover, it will be helpful in managing carbon revenues and structuring programmes and policies to take into account the potential volatility of these revenues (World Bank, 2019).

The World Bank (2019) also argues that understanding the objectives and impacts of carbon pricing is essential for ensuring a coherent framework for revenue use. Besides motivating firms, consumers and investors to internalize the negative effects of GHG emissions into production, consumption and investment practices, carbon pricing also has other benefits and co-benefits, such as improved health, mobility and resilience as well as improvements in other environmental outcomes. Policy makers should, however, take into account some adverse effects of carbon pricing when allocating carbon revenues. A carbon price's negative impacts tend to be concentrated in certain sectors or among certain consumers, suggesting that revenue could be used to offset these effects (World Bank, 2019).

Finally, the World Bank (2019) emphasizes that a successful revenue distribution network is part of a proper fiscal policy that pursues wider objectives related to efficiency, long-run growth, and equity. An *efficient* fiscal policy is able to internalize the positive and negative externalities and reduces distortion and administrative costs. *Long-run growth* could be ensured in fiscal policies where they smooth the economic cycles, increase innovation and productivity growth and keep debt levels sustainable. *Equity* in a fiscal policy could be ensured through reduction of inequality by redistributing income from high-income groups to low-income groups, by addressing disadvantage at a regional level or address the costs of economic transition, and by supporting development and economic inclusion (World Bank, 2019).

3.4 Results for subtask 7 – GHG Pricing Mechanism: Revenues and Expenditure

3.4.1 A review on revenue collection and distribution in other sectors

3.4.1.1 Background

It is expected that carbon prices and pricing mechanism coverage will increase in the future in order to meet climate targets (World Bank, 2016). As carbon pricing expands in the coming decades, significant flows of carbon revenue could be available to support investment in the developing world (World Bank, 2019). By employing the world-systems theory, Ciplet et al. (2022), have tried to clarify the relationship between climate finance and climate justice and analyse the uneven geographies of climate finance. Their analysis demonstrates the importance of an equitable revenue distribution mechanism in order to complete the effects of future maritime carbon pricing mechanism.

In addition to being an instrument for efficient climate mitigation, carbon pricing policies could also be viewed as an instrument for generating revenue for general fiscal purposes. Some experts argue that the use of carbon pricing could be even more effective than the regulatory instruments in reducing emissions, as well as providing incentives for the development of clean technology and promoting international carbon markets (De Mooij et al., 2012). Strategically allocating generated carbon revenue can provide a balance among social, economic, environmental and political concerns that arise from implementing a carbon pricing scheme (Narassimhan et al., 2018). For instance, through timely updates and tightening of the regional cap, the US Regional Greenhouse Gas Initiative (RGGI) has been able to transform the carbon price 'penalty' into a tool for supporting public benefits. It has been demonstrated that carbon revenue recycling can play an important role in sustaining carbon pricing as a climate mitigation strategy (Raymond, 2016; as cited in Wiese et al., 2020). Taxes on carbon can provide a substantial new source of revenue which is particularly helpful during times of fiscal consolidation. In many countries, an appropriately scaled carbon tax would generate approximately 1% of GDP (De Mooij et al., 2012).

The actual level of carbon revenue and the predicted range of generated revenue from different carbon pricing mechanisms worldwide are very diverse, mainly due to different carbon price levels, methods of revenue generation and regional policies. According to a prediction in 2012 by De Mooij et al. (2012), a carbon price of $25 per tonne of CO_2 in developed economies, for instance, could raise about $250 billion in 2020. In 2015 alone, carbon pricing policies generated $26 billion in revenues worldwide (World Bank, 2016). The EU ETS generated about $17 billion in auctions between 2012 and 2016 (European Commission, 2017, as cited in Narassimhan et al., 2018). The International Monetary Fund (IMF, 2019) estimates that a carbon price of $70 per tonne of CO_2 could generate revenues of 1–3% of gross domestic product (GDP) by 2030 in most countries considered, and around 2–4% of GDP in major developing countries, including China, India, and South Africa. In terms of revenues, the EU ETS is the largest source because of the size of the market. It is followed by the carbon tax in France, the California ETS and the carbon taxes in Sweden and

Japan. Despite their smaller absolute size, carbon prices often play an important role in other jurisdictions' revenue streams (World Bank, 2019). It is expected that by 2050 annual resource flows from carbon markets will reach $1.86 trillion, with trade of 4,310 million tonnes of CO_2. There is the possibility that Africa will be the largest net supplier, receiving financial inflows of approximately $1 trillion a year, which corresponds to about 5% of its projected GDP in 2050 (World Bank, 2019).

Due to the diverse methods and outcomes in revenue generation across various carbon pricing mechanisms, the approaches to revenue recycling and associated expenditure levels exhibit significant variability. For instance, out of $2.7 billion revenue generated in RGGI between 2009 and 2014, at least 25% must be used for 'consumer benefit or strategic energy purpose' by participating states, 42% for energy efficiency programmes, 11% for bill assistance to low-income residents, 9% for GHG abatement, 8% for renewable energy development, 4% for programme administration and 1% for RGGI management (Ramseur, 2015 as cited in Narassimhan et al., 2018). From $17 billion revenue of EU ETS between 2012 and 2016, at least 50% was earmarked for climate- and energy-related purposes and for retrofitting existing infrastructure (European Commission, 2017 as cited in Narassimhan et al., 2018). The state of California generated $3.385 billion in revenue through 2017 and has invested the revenues into high-speed rail, low-carbon transit, weatherproofing of low-income housing and environmental conservation (CCI, 2017, as cited in Narassimhan et al., 2018). Around 70% of global revenues from cap-and-trade are allocated to "green spending" as of 2014 (Carl and Fedor, 2016).

There are some carbon tax systems that use direct returns of carbon-pricing revenues to businesses or individuals through tax breaks or rebates, but this is not common among cap-and-trade systems. Only two of seven global cap-and-trade systems (9% of revenues) directly return any revenues (Carl and Fedor, 2016). As a result of California's ETS, just over half of its auction revenues are returned to households through rebate checks. Another regional carbon revenue system available in the United States is the RGGI which reduces electric utility rates by 12%, second only to California in terms of the amount of money recycled from cap-and-trade programmes. Only seven of thirteen carbon tax schemes recycle their revenues which accounts for around 44% of total revenue. Generally, revenue-returning tax systems tend to have higher per capita burdens. British Columbia's revenue-neutral carbon tax recycles 100%

of its revenues through corporate and individual tax breaks, as well as rebate checks for low-income residents. Notably, Switzerland's carbon tax returns two-thirds of its revenues to residents and businesses through flat cheques mailed to all individuals and business payroll tax rebates (Carl and Fedor, 2016). Allocating all tax revenues exclusively to environmental programmes is generally not preferable (e.g. subsidies for clean technologies, climate finance, research and development or compensation for industry). It is important to recognize that the revenue generated by a carbon tax is unrelated to the socially-desirable level of expenditures for environmental programmes. To justify these programmes, some experts believe that it is essential to address additional market failures, i.e. they should generate economic benefits comparable to those derived from alternative revenue uses (De Mooij et al., 2012).

3.4.1.2 Revenue sources

Traditional revenue sources include value-added tax (VAT), corporate income tax (CIT), personal income tax (PIT) and property taxes. There is widespread agreement that the VAT has proven to be a relatively efficient source of revenue and generates less distortion than many other taxes. As a component of a product or service's price, VAT is assessed incrementally and levied on the price at each stage of production, distribution or sale to the end consumer. The CIT is not a likely candidate as a source of additional revenue and the effort of many countries has led to significant reductions in statutory CIT rates. There is general agreement that PITs are essential to achieving equity objectives (since the average tax rate may rise with income levels) and might have some potential to increase revenues in some developed economies, although rate increases are unlikely. For a number of countries, recurrent property taxes represent an attractive source of additional revenue. In many developed economies, the increased use of property taxes is strongly supported by arguments related to efficiency and fairness (De Mooij et al., 2012).

Innovative sources of finance include carbon pricing, removing fossil fuel subsidies and financial sector taxes. According to De Mooij et al. (2012), climate finance policies that include comprehensive carbon pricing policies, such as a carbon tax or emission trading with full auctioning of allowances, are widely believed to be a promising option. Carbon pricing policies can serve both as instruments for efficient climate mitigation and as a means of raising revenues for general fiscal purposes. Some experts argue that in terms of reducing emissions and providing incentives for the development of clean technology and promoting international carbon markets, carbon pricing could be more effective than regulatory instruments (De Mooij et al., 2012). Reducing fossil fuel subsidies in developed economies has attracted particular attention as a source of revenue for climate finance. According to a study conducted by OECD, fossil fuel subsidies in developed economies amounted to about $40-$60 billion annually between 2005-2010 (De Mooij et al., 2012). In some countries, in order to raise funds for climate finance, new taxes have been proposed on the financial sector. Since the 2008 financial crisis, several countries have introduced "bank taxes" on some subset of banks' liabilities or typical assets. There are two types of financial transactions taxes: a broad-based financial transaction tax (FTT) that is imposed on a wide range of financial transactions and a financial activities tax (FAT) that is imposed on a financial institution's wages and profits (De Mooij et al., 2012).

3.4.1.3 Using revenue from taxes and auctions

Aside from providing incentives for reducing emissions, carbon taxes and auctioned allowances also generate revenue (De Mooij et al., 2012). In principle, the distribution of revenues from auctioned allowances or carbon taxes can enhance policy efficiency, reduce regressivity in the financial burden distribution, and/or enhance political feasibility and stability. However, these benefits are contingent upon how the revenue is recycled (De Mooij et al., 2012). The World Bank (2019) argues that "the use of carbon revenues can be a powerful tool in building support for carbon pricing and for pursuing environmental, economic, and social objectives". This section presents possible methods of distributing carbon revenue, based on literature examining different industrial sectors.

Containing the burden on target groups

There is a common concern regarding carbon pricing, regarding the impact it has on low-income families and/or the competitiveness of certain industries, referred to as target groups (De Mooij et al., 2012; IMF, 2019; World Bank, 2019). A practical approach would be to modify the taxation system by using some revenue to compensate target groups. By increasing the income threshold level below which no tax is due in countries where low-income households pay income taxes or payroll taxes, these households will likely receive an increased rebate compared to the prosperous classes. A transitory subsidy for production or the adoption of energy-saving technologies could be provided to vulnerable firms in order to offset the detrimental effects of higher energy prices on their competitiveness. These compensation schemes, however, carry the risk of sacrificing some of the potential economic benefits associated with the recycling of carbon tax revenues (De Mooij et al., 2012). As a result of the economic impacts and burden on target groups, several design strategies have been developed as a means of containing potential cost increases, such as exemptions, preferential tax rates, rebates, gifted allowances (De Mooij et al., 2012) or feebate systems (World Bank, 2019).

- ***Exemptions*** are a common strategy for lowering tax burdens. Exemptions include (1) exempting all emissions from sources with emissions that are below a certain threshold, (2) excluding emissions from sources that are covered by another policy to prevent double taxation, (3) exempting emissions from sources that are deemed unacceptably vulnerable to cost increases and (4) exempting emissions where international legal issues pose special implementation challenges. Despite the fact that the first two types of listed exemptions are generally not expected to pose significant cost effectiveness concerns, the third and fourth types of exemptions can raise significant issues. Those facilities that receive exemptions are not subject to any controls on GHG emissions under that instrument which eliminates their incentive to reduce emissions (De Mooij et al., 2012).
- ***Preferential tax rates*** are even more common. Norway, for example, offers reduced rates to the pulp and paper industry, the fishmeal industry, domestic aviation, and domestic shipping. Similarly, a lower rate of tax is applied to manufacturing, agriculture, cogeneration plants, forestry and aquaculture in Sweden (De Mooij et al., 2012). Energy price adjustments mentioned by Carl and Fedor (2016) which are used in California, the RGGI, and Sweden could be classified within this category, although they could be criticised for dampening the effective carbon price signal which is generally the policy's original intent.
- ***Rebates*** are another possibility (with mixed results) for reducing the cost burden on vulnerable firms. As an example of rebates in action, the Swedish Nitrogen charge system is characterized by a high charge rate with the revenue from this tax not retained by the Government but rather rebated to the emitting sources. This

minimizes the impact of the tax on competitiveness. Although the tax is collected based on NO_x emissions, it is rebated based on energy production. The result of this system is that plants emitting little NO_x per unit of energy are rewarded and plants emitting more NO_x per unit of energy are penalized. As a result of this approach, NO_x emissions per unit of energy produced are reduced, but the amount of energy produced is not reduced. Therefore, taking into account the growing rate of energy demand, it reduces fewer total emissions than an unrebated tax (Sterner and Turnheim, 2008, as cited in De Mooij et al., 2012). Carl and Fedor (2016) highlight that the rebates granted specifically to low-income or other particularly "impacted" households which are used in the Australia and British Columbia schemes.

- ***Gifting*** can occur in either a carbon tax system or an ETS. As part of a tax system, only emissions that exceed a gifted threshold are taxed, a strategy that is adopted by some European effluent charge systems. Alternatively, in a cap-and-trade system, part of the allowances can be gifted (free of charge) to certain sectors. In either case, the sector does not have to bear the financial burden of paying for gifted emissions, although it is not relieved of its obligation to reduce GHG emissions as an exemption does. Due to their large and increasing opportunity costs, gifting of allowances has become less common as carbon pricing experience has grown. There is usually a decline in the proportion of gifted allowances over time in systems that grant them. In the EU ETS, for example, it is planned to auction off 20% of all EU allowances in 2013, with a gradual increase aiming to auction off 70% by 2020. By 2027, full auctioning will be achieved. A very small amount of gifting is already occurring in the US RGGI. In the RGGI, about 86% of CO_2 allowances are offered at auction, while approximately 4% of CO_2 allowances are sold at a fixed price (De Mooij et al., 2012).
- ***Feebate systems***, where revenue is raised from the most emission-intensive businesses and returned to more efficient businesses, to maintain incentives and strengthen the overall profitability of the industry (World Bank, 2019). Feebate mechanisms provide a means of protecting pioneer industries in the green transition and addressing concerns regarding their competitiveness in the market. Additionally, feebate is one of the most effective approaches in avoidance of carbon leakage. Carbon leakage refers to a shift of carbon-intensive industrial production, investment,

and operations from markets with carbon pricing systems to markets with less stringent carbon regulations (World Bank, 2019).

Using revenue to lower other taxes

Economic distortions caused by the broader tax system are a major concern in carbon pricing mechanisms. There is evidence that income taxes, payroll taxes and general consumption taxes tend to reduce (moderately) labour force participation and effort on the job, as well as shifting production to the informal sector in some cases. In order to minimize these effects, carbon pricing revenues can be used to reduce other taxes that distort incentives for work or investment (De Mooij et al., 2012; World Bank, 2016); however, this can lead to a reduction in net revenue used to finance climate action. This is the simplest way to use revenues to boost economic efficiency. By reducing taxes on items that distort the broader economy, the overall cost of the policy is also reduced substantially. Moreover, this revenue recycling can reduce, at least to some extent, the regressivity of the distributional burden of the costs, depending on which distortionary taxes are reduced. A tax on labour income, for example, distorts the labour market by reducing the rewards associated with participation in the labour force and effort. An increase in corporate income tax distorts the capital market as a result of suppressing capital accumulation below levels that would otherwise maximize economic efficiency. As a result, reducing these taxes by using climate policy revenues has broader economic benefits. Carbon taxes can substantially reduce policy costs if revenues are used in a socially beneficial manner, such as by reducing distortionary taxes elsewhere in the economy or by funding socially desirable expenditures (De Mooij et al., 2012).

Carbon revenue could be returned to consumers in a variety of ways, including lump-sum cashback or reductions in income, employment, and capital taxes (Wiese et al., 2020). Revenue recycling has been undertaken in a variety of ways by different countries. In Sweden and Finland, revenue has been recycled primarily through the reduction of income taxes. The Danish and United Kingdom Governments, on the other hand, have primarily used revenues to reduce employers' social security contributions. The revenue has primarily been used to lower the personal, corporate and small business income taxes in British Columbia, Canada. More than half of the revenue generated by the Australian plan will be used to reduce the cost burden on households. Tax and transfer systems are utilized to deliver cash assistance. The statutory tax-free threshold is tripled to support low- and middle-income individuals. By reducing taxes, increasing pensions and providing cash transfers, the government of Australia intends to at least offset any expected average price impact from the carbon price on low-income households (De Mooij et al., 2012). Baranzini and Carattini (2017) name this method of carbon revenue recycling as "social cushioning". Corporate tax cuts and income tax cuts could be classified in this category. "Corporate tax cuts", either on profits or payroll taxes, were granted to businesses in Australia, Sweden, Norway, British Columbia, Denmark, Finland and Switzerland's carbon tax, and "income tax cuts" granted to individuals in Australia, Sweden, British Columbia, Denmark, and Finland (Carl and Fedor, 2016).

Promoting renewable energy and energy efficiency

The promotion of renewable energy and energy efficiency is another option for the distribution of carbon revenue. Under a carbon tax, this strategy would reduce emissions further, while under an ETS it may instead result in lower allowance prices depending on what emissions reductions are covered by the cap. It is estimated that approximately 60% of the tax revenue in Denmark is returned to industry, however some 40% of the tax revenue is used for environmental subsidies. In Quebec, Canada, revenue from the carbon tax is deposited in a "green fund," which supports measures that are expected to result in the greatest reductions in GHGs or avoidance of them (Sumner et al., 2011, as cited in De Mooij et al., 2012). The RGGI also tends to concentrate its revenue on promoting energy efficiency. As well as being more cost-effective than renewable resource investments in those States, these investments have even resulted in lower electricity prices that can reduce the policy's regressive impact. In addition to raising the competitiveness of several large industrial facilities, these incentives have increased political support to ensure their viability (De Mooij et al., 2012). The World Bank (2016) calls this revenue earmarking as "transitional support to industry" that may support R&D activities and energy efficiency investment and innovation.

Wiese et al. (2020), by underlining the increasing trend of the EU ETS revenues due to tightening of the cap, argue that in 2017 only 21.4% of total revenues have been strategically invested in energy efficiency programmes in EU Member States, while a huge potential could be released by investing in this area as it is proven in Germany and Czechia. Carbon revenues (for example, those generated through auctions) can be invested in energy efficiency to achieve a greater share of cost-effective emissions reductions. Wiese et al. (2020) argue that "non-price barriers to energy efficiency cannot be overcome by a pricing policy alone". Therefore, they argue that it is necessary to develop energy efficiency programmes that address the behavioural, financial and legal barriers to energy efficiency in order to take advantage of the greatest portion of the potential for reducing emissions at the lowest cost. Meanwhile, by investing carbon revenue in energy efficiency, the impact of carbon pricing on end-users' energy bills would be mitigated (Wiese et al., 2020). In addition to the substantial benefits of reducing air pollution and energy poverty, Thema et al. (2019) conclude that investments in energy efficiency in EU countries can result in at least 50% reductions in energy costs. In 2017, Belgium, Czechia, Croatia, Hungary, Italy and Latvia reported that they were planning to strategically invest between 50 and 100% of their domestic auction revenues in the improvement of energy efficiency (Wiese et al., 2020). In the north-eastern United States, the RGGI cap-and-trade system uses most of the auction revenues to fund energy efficiency programs among end users. This has the effect of not only reducing emissions but lowering the cost of electricity for many consumers (Wiese et al., 2020).

Offsets

According to Ramseur (2015), "an offset is a measurable reduction, avoidance, or sequestration of GHG emissions from a source not covered by an emission reduction program". As opposed to approaches discussed in Section 1 which aim to alleviate the burden on target groups, allowing offsets is an effective way to reduce costs for all participants by increasing the supply of reduction options available to groups not otherwise covered by the carbon pricing programme. Although offset credits can be permanent components of a carbon pricing programme, they can also serve as a transitional strategy. It is likely that offset credits will represent the best opportunity to reduce emissions for countries that remain outside the cap. This particular type of offset would no longer be necessary once all countries were subject to the pricing regime (De Mooij et al., 2012).

In carbon pricing programmes, emission "offsets" are commonly used to reduce the financial burden on emission sources outside these programmes. An offset programme may result in larger reductions in total emissions under a carbon tax, however it will not have any effect on total emissions reductions under a cap-and-trade system. Yet the challenge is to ensure that the emission reductions credited outside the formal programme can be measured and would not have happened anyway (without the offset credit). The majority of programmes limit offsets because of concerns about credibility but newer approaches attempt to differentiate between more credible offsets (which are allowed) and less credible offsets (which are rejected) (De Mooij et al., 2012).

To ensure the effectiveness of an offset programme, the reduction must be quantifiable, enforceable and additional. It is important that all these requirements must be met in order to develop an effective offset programme. In addition, the cost of ensuring valid offsets is high due to the high transaction costs involved. In addition, developing countries may well be reluctant to undertake projects on their own if an offset mechanism such as the clean development mechanism (CDM) can be used to offset their costs. CDM is the offset market created by the Kyoto Protocol that is going to be substituted by the Sustainable Development Mechanism, a new international carbon market under the 2015 Paris Agreement and governed by the United Nations (Green, 2021).

According to some experts, there are two possible effects of offsets on overall reductions. In the first instance, the use of offsets may diminish the actual reductions achieved by a carbon pricing policy. To demonstrate the quality of an offset methodology and its contribution to additional reductions, as well as the number of credits claimed for that project or protocol under a specific carbon pricing policy, it is necessary to conduct an assessment. Secondly, it should be noted that regulated entities that rely more heavily on offsets will have fewer in-situ reductions. This would explain the relatively small reductions in those entities (Green, 2021). Despite this, offsets have been an important component of most ETSs to date. The EU allowed up to 50% of EU wide reductions to come from offsets in Phases 2 and 3, largely from the CDM of the Kyoto Protocol (Green, 2021). Nevertheless, the CDM was plagued by numerous problems. According to one study, 73% of all emissions reductions generated by the CDM between 2013 and 2020 may be overestimated and may not represent additional reductions (Cames et al., 2016, as cited in Green, 2021).

In light of the above-mentioned barriers, and as a result of doubts regarding the validity of an offset plan, most programmes are now considering ways to limit their use. For example, Germany announced in 2011 that it would not allow any offsets to be used to achieve its reduction goals. It is also believed by observers that California will not accept CDM-certified emission reductions into its emissions trading programme. A similar limitation has been imposed by the EU on the size and scope of offsets eligible for reimbursement (Green, 2021).

Financing climate and environmental projects

Tax revenue earmarked for environmental purposes has been discussed in the literature on many occasions. In survey-based research by Baranzini and Carattini (2017), 60% of the respondents would like to see the tax revenues used to finance environmental projects as the highest priority. Similarly, Narassimhan et al. (2018) argue that revenues generated from auctioning allowances could be used in additional climate change mitigation. Despite the fact that a carbon price can encourage emissions reductions, there can be market failures that prevent participants from responding effectively to price signals. The private sector's inability or unwillingness to invest sufficiently in low-carbon activities can result in a number of market failures. This situation may allow governments to provide funding for these investments from carbon revenues. By investing carbon revenues in climate mitigation policies, additional emissions can be reduced and the acceptance of carbon pricing can be boosted (World Bank, 2019).

Construction of new infrastructure and retrofitting existing infrastructure

Two new funds will be established by the EU using revenue generated by allowance auctions: an *innovation fund* that will extend existing support for demonstrating innovative technologies, and a *modernization fund* that will facilitate investments in modernizing the power sector and increasing energy efficiency (Meadows, 2017, as cited in Narassimhan et al., 2018). Urban infrastructure plans are a suitable target for attracting these investments. In this direction, ITF (2023) considers earmarking congestion charging revenues for improving public transport and active mobility. Congestion charges may be accepted more readily if the revenue generated is directed toward improving public transportation services and making walking and cycling safer in metropolitan areas. As a result, the modal shift toward more sustainable modes of transportation will be facilitated. Rather than earmarking revenues for specific projects or purposes, it is recommended that governments allocate revenues to broader programmes. As a result, funds will be able to be directed to their most productive uses, providing needed flexibility (ITF, 2023).

Administrative costs

According to Narassimhan et al. (2018), part of revenues generated from auctioning allowances could be used in reducing EU ETS administrative costs. In 2017, 0.3% of EU ETS auctioning revenue was earmarked to coverage of administrative and management expenses

(Wiese et al., 2020). The RGGI programme has earmarked around 5% for administrative and management costs (Ramseur, 2015). A rough rule of thumb is that the administration of a carbon pricing mechanism may require up to 5% of carbon revenue (De Mooij et al., 2012).

Funding of research and development (R&D)

In 2017, 1% of EU ETS auctioning revenue was earmarked for funding of research and development (R&D) for clean technologies and energy efficiency and 0.1% for the demonstration of R&D projects for reducing emissions and for adaptation (Wiese et al., 2020). As a result of the split incentives (market failure) rooted in knowledge or innovation spillovers (IMF, 2019), firms and innovators may underinvest in R&D. It can be argued that knowledge and innovation are public goods with positive externalities, since innovative firms that develop new technologies create benefits for other companies and incur costs at the same time. The innovative firm lacks the incentive to increase investment when the benefits are shared with others. Governments can address this underinvestment by providing funding for R&D. For instance, through green subsidies and R&D support, Japan's carbon tax was explicitly designed to fund renewable energy and energy efficiency programmes, including lithium-ion batteries, distributed energy generation and CO_2 capture and storage (World Bank, 2019).

Adaptation to the impacts of climate change

Some literature argues that it is possible to address the collective challenges of climate change in a fair and efficient manner through transfers from developed to developing countries (De Mooij et al., 2012; Word Bank, 2016; Parry et al., 2018; IMF, 2019). In light of climate change, such transfers are particularly salient from an ethical perspective. Developing economies may need to adapt extensively to limit the harmful effects of climate change (perhaps in the order of $90 billion a year by mid-century, according to the World Bank (2016), and may suffer significant residual damage as well. Adaptation to climate change (e.g. water defences) may be funded through revenues where private sector investments would otherwise not be sufficient (De Mooij et al., 2012). In 2017, 1% of EU ETS auctioning revenue was earmarked for adaptation to the impacts of climate change (Wiese et al., 2020).

Flow into national budgets

According to De Mooij et al. (2012), the revenue from carbon pricing does not necessarily have to be earmarked for climate finance. One possibility is the flow of revenues into national budgets (Parry et al., 2018; De Mooij et al., 2012). As a means of reducing overall policy costs, carbon revenues could be utilized to alleviate distortions caused by the broader fiscal system, reduce government debt and/or fund valuable government expenditure. According to the World Bank (2019), carbon revenues allocated to general government revenue are distinct from most other sources of revenue and are linked to specific spending programmes or tax cuts. The revenues that are not subject to these restrictions are allocated to the general government budget, which can be spent for particular purposes based on government priorities. In order to link revenue to these particular purposes, there are two methods available: legal earmarking, which involves a legislative or executive action linking revenues to expenditure initiatives, and hypothecation, which is the communication of the links between revenues and expenditures without an enforcing legal framework (World Bank, 2019).

Cross-cutting measures

In 2017, 2% of the EU ETS auctioning revenue was earmarked for cross-cutting measures (Wiese et al., 2020). Catalysing private climate finance is an innovative approach that could be classified in this category. In order to encourage private initiatives, developed economies may need to establish strong and credible carbon prices, (maybe) in conjunction with similar pricing elsewhere, or with international offset provisions that also cover firms in developed economies to take advantage of abatement opportunities in developing economies in lieu of paying carbon taxes or purchasing emission allowances (De Mooij et al., 2012). The financing of socially desirable public projects may also be classified as part of this category, since it could be an ad hoc mechanism in different countries for a specific period. In developing economies, especially those suffering from capital shortages, revenues could be used to finance social public projects such as education, infrastructure, health, etc. (De Mooij et al., 2012).

3.4.2 Maritime industry

3.4.2.1 Projected carbon revenue

An important issue in the debate over carbon pricing mechanisms is the generation of revenue and its distribution. Based on different scenarios, maritime experts and economists have proposed a range of carbon prices for achieving decarbonization targets in the shipping industry, as shown in table 24.

Table 24. An estimation of annual tax revenue in 2030 and 2040 checkpoints and revenue range between 2025 and 2050

Source		Carbon price ($) per tonne CO_2	Yearly Revenue		Cumulative revenue range
			2030	2040	2025-2050
Proposals based on candidate measures (e.g. levy)	ICS IMSF&R proposal (IMO, 2023c)	**$12.5**	7.3 b$*	2.7 b$*	-
	Marshall Islands and Solomon Islands proposal	Starting with **$100** in 2025 and from 2030 onward **$250-300**	146-175 b$*	55-66 b$*	-
	Maersk (Euractiv, 2021)	**$150**	88 b$*	33 b$*	-
	(Trafigura, 2020)	**$250-300**	146-175 b$*	55-66 b$*	-
Academic studies based on technical/ scientific assess-ments	(Lagouvardou, Psaraftis, and Zis, 2022)	**$150-400**	88-234 b$*	33-88 b$*	-
	(Parry et al., 2018)	**$75** in 2030 and **$150** in 2040	76 b$	155 b$	-
	(Baresic et al., 2022)	**$191** (zero emissions in 2050)	112 b$*	42 b$*	$1 trillion - $2.6 trillion
	(MMM Center, 2021)	**$230**	135 b$*	50 b$*	$1.8 trillion (after deduction of green fuel production cost)
	(Smith, 2020)	**$50-250** (50% emission reduction by 2050, in case of fully re-investing in zero-carbon fuels and technologies)	29-146 b$*	11-55 b$*	-
A conclusion of previous studies by (Dominioni and Englert, 2022) and (Dominioni et al., 2023)			40-60 b$ yearly		$1 trillion - $3.7 trillion

Note: In the calculation of the yearly revenue marked with (*), the life cycle emissions (WtW) mentioned in table 25 has been considered.

Table 25. Maritime CO2 emission predicted for 2030 and 2040 checkpoints based on IMO net zero strategy. Source: Class NK, 2023

GHG emissions (Million tonnes $CO_{2\text{-}eq}$)	2008 (Base year)	2030 (1st check point: 20% reduction versus 2008)	2040 (2nd check point: 70% reduction versus 2008)
Life cycle GHG emissions (WtW)	731	585	219
GHG emissions (WtT)	110	88	33
GHG emissions (TtW)	621	497	186

Considering the adoption of emerging zero or near-zero GHG emission fuels and electrical energy in ship propulsion, the WtW carbon emission can be considered in the revenue calculations. In case of electrified ships or use of zero or near-zero GHG emission fuels with least or no emission on board, the application of TtW is meaningless.

3.4.2.2 Revenue collection methods

The carbon tax (levy) could be collected in the following ways:

- Collection by flag administrations (the marine regulator under which the ship operates) (Parry et al., 2018).
- Collection by port state administrations (Parry et al., 2018).
- Collection centrally by an international institution (Parry et al., 2018).
- Collection by bunker suppliers (Marshall Islands and Solomon Islands, 2021; Wemaëre et al., 2023; Nuttall et al., 2021) and International Fund by Cyprus et al. (IMO, 2009).
- Payment by each individual ship directly to its electronic account in an international GHG Fund, recommended in the Japan LIS proposal (IMO, 2010a) and EIS proposal (IMO, 2011)

Masodzadeh et al. (2022b) argue that tax collection through the network of bunker suppliers would ensure tax payment since tax is collected at the sale point. Furthermore, the administrative burden is distributed among bunker suppliers and a GHG Fund would deal with a limited number of bunker suppliers rather than negotiating with a large number of ships individually (Masodzadeh et al., 2022b).

3.4.2.3 Potential revenue use

MEPC 80 agreed on terms of reference for the comprehensive impact assessment of the basket of candidate mid-term measures, with the Steering Committee agreeing to proposed areas for revenue disbursement for modelling potential impacts on States and the fleet as follows: RD&D; Capacity-building and negative impact mitigation; Address disproportionately negative impacts (DNI) as appropriate; Reward for eligible fuels; General GHG mitigation and adaptation; Equitable transition; and Administration. The Steering Committee agreed also that any final decision on how to disburse potential revenues on the basis of a maritime GHG emissions pricing mechanism would be subject to a discussion by MEPC. No further agreement was made on the categorization of in-sector and out-of-sector revenue distribution areas.

A number of countries and the shipping industry have submitted technical proposals for a levy, suggesting that its revenues might be used to reduce the carbon footprint of the shipping industry, as well as to support the climate action plans of developing countries (e.g. Argentina et al., 2022; Japan, 2021; ICS & Intercargo, 2021). According to the literature review, there are important implications in determining who pays and who receives the proceeds from a potential levy since some countries rely heavily on the maritime sector for their livelihoods and trade (Wemaëre et al., 2023). While a number of maritime experts and economists have proposed some thresholds for a GHG emissions pricing mechanism and revenue ranges, based on different scenarios, there is limited literature addressing revenue recycling. It has been found that maritime experts believe that the gathered funds through any maritime carbon pricing mechanism can be spent in-sector to mitigate CO_2 emissions in the shipping industry (e.g. Koesler et al., 2015). In contrast to direct shipping sector stakeholders, who prefer to recycle all revenues within the industry, several IMO Member States and observers have supported that a portion of revenues can be distributed outside of the industry. However, it is premature to discuss what proportion can be recycled in the "outside the sector" segment (Wemaëre et al., 2023). In addition, it may be difficult to define a border between in-sector and out-of-sector activities. When considering the lifecycle of technologies and the well-to-wake carbon footprint of zero or near-zero GHG emission fuels, it is imperative to consider that only a part of these technologies and zero or near-zero GHG emission fuels that are produced in land-based industries could be used in marine environments. It is noteworthy that in the production of zero or near-zero GHG emission bunker fuels, 87% of investments may be made in land-based industries, and the remaining 13% is needed for ship-specific investments (Krantz et al., 2020). By focusing on revenue recycling in some carbon pricing proposals (e.g. ICS and Intercargo, 2021), the main emission reduction effect does not appear to be a result of the carbon price but rather from how revenues are distributed.

Experts in Carbon Market Watch (2021) argue that "If the revenues are earmarked to too many causes and concerns, they risk becoming watered down and ineffective. Therefore, carbon pricing revenues can be invested in a limited number of areas''. They highlight the following areas for revenue expenditure: financing in-sector climate action (e.g. proving new technologies, retrofitting existing ships, shoreside electrification and investing in R&D, sustainable supply and infrastructure related to renewable fuels); addressing equity and fairness concerns in response to the CBDR&RC principle; and alleviating socio-economic concerns (e.g. financing re-skilling schemes for workers).

As shown in figure 55, proper recycling of revenue from a GHG emissions pricing mechanism to support activities in-sector and out-of-sector could not only help to achieve shipping decarbonization goals but also pave the way to achieving broader climate aims and promote a more equitable outcome. According to the World Bank (2023), since overall and global climate change goals are concerned, some of the most cost-effective options to combat climate change are likely to be unrelated to maritime transportation. This illustrates the importance of the out-of-sector expenditures of maritime carbon revenues.

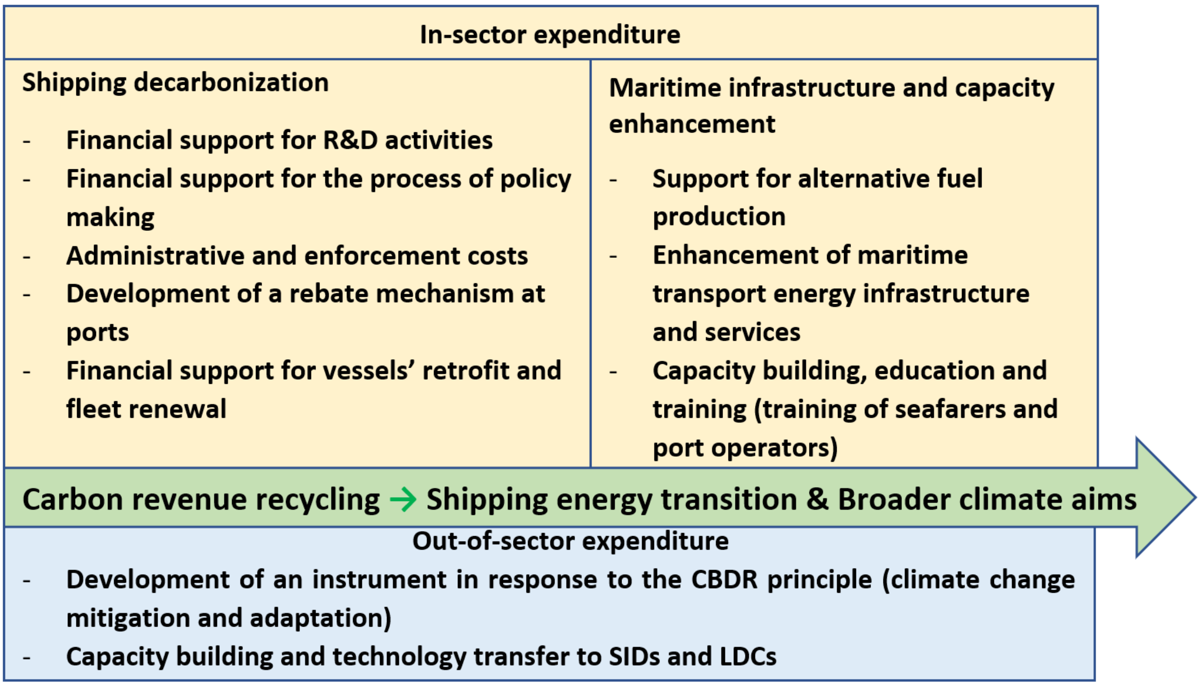


Figure 55. Carbon revenue expenditure areas. Source: Based on World Bank (2023)

3.4.2.3.1 In-sector distribution

Financial support for research, development and deployment (R&D) activities

According to the literature (e.g. Parry et al., 2018; Dominioni et al., 2023), in order to ensure the availability and maturity of technologies at the predicted time, it is essential to provide financial support for RD&D projects at universities, research institutes and laboratories. To a high extent, the effectiveness of a future carbon pricing mechanism in shipping depends on reinvestment in the decarbonization of shipping via RD&D. Almost all carbon pricing proposals have clearly highlighted that part of the collected revenues shall be spent on research and development (e.g. ICS and Intercargo, 2021 and Marshall Islands and Solomon Islands, 2021). According to the Marshall Islands and Solomon Islands, funds for research and development could be allocated through a mechanism similar to the International Maritime Research Board (IMRB).

Financial support for the process of policy making

The process of policy making requires highly reliable and precise data. Policymakers can use the data analysis results to guide and develop evidence-based policies and strategies. Insights derived from the data are useful in identifying key issues, understanding the potential impact of different policy options and assessing the feasibility and effectiveness of proposed policies. For instance, in designing a framework and set of criteria for revenue distribution, there might be a crucial need for precise data from different in-sector maritime stakeholders as well as out-of-sector national actors in the form of a national dataset (Dominioni et al., 2023). According to the World Bank (2023), in recognizing the eligibility of States to receive carbon revenues to support their investment in production and distribution of zero or near-zero GHG emission fuels, there has been a data shortage affecting some countries. Many countries have been unable to identify potential investment opportunities due to a lack of data. Strategic planning and decision making require data, at an international and a national level, in order to promote informed dialogue across levels of government and sectors of society (OECD, n.d.). However, such studies and data collection can pose a financial burden, especially if they have never been conducted before at a national level and must be initiated and collected for a specific purpose (UNCTAD, 2013). The IMO GHG TC-Trust Fund may be able to provide support for the cost of such feasibility studies. UNFCCC (2024) has highlighted financial mechanisms that serve the Kyoto Protocol and the Paris Agreement, such as the Global Environment Facility (GEF) and the GCF, that may be able to support developing countries, LDCs and SIDS.

According to Bach and Hansen (2023), "the current administrative organisation of the IMO would have very limited financial and human resources". As a result, it is evident that a greater number of professionals are required to support the decision-making process in IMO as well as conducting high-quality policy pre-studies. As an example, Masodzadeh et al. (2024a) recommend a live carbon-tracking mechanism (voyage-based data collection system) that could be financially supported by the future IMO GHG Fund (Masodzadeh et al., 2022b), in accordance with the importance of accurate datasets in policy making.

Administrative and enforcement costs of the carbon pricing mechanism

Administrative or running costs of the future maritime carbon pricing mechanism have been highlighted in some carbon pricing proposals such as Argentina et al. (2022) and Marshall Islands and Solomon Islands (2021). According to Masodzadeh et al. (2022b), the running costs of the future carbon pricing mechanism (e.g. in case of a GHG levy) can include the costs associated with the establishment and operation of IT infrastructure, an IMO GHG Fund administrative set up, data collection, tendering, audit/inspection cost, compensation for bunker suppliers for tax collection and transfer, payments to data verifiers for data processing, and payments to the PSC for energy inspections at ports. Considering this cost breakdown and based on a levy of $50 per tonne of bunker fuel that generates a revenue of more than USD 11 billion, they estimate 3% of revenue ($330 million) can be spent on carbon pricing implementation.

Development of a rebate mechanism at ports

Development of a rebate mechanism could generally boost the motivational effect of the carbon pricing mechanism, and consequently enhance its decarbonization results (Muresianu, 2021). According to Pomerleau and Asen (2019), 'rebates make the tax code significantly more progressive'. A recommendation could be a rebate mechanism at ports in the form of a global port incentive programme (PIP) focused solely on CO_2 reduction.

Currently, PIPs are voluntary and a limited number of ships and ports participate in these programmes. CO_2 reduction is not the core objective of most PIPs; furthermore, the financial incentives offered are only very marginal and are not encouraging a change in behaviour. As a result of the lack of harmony between PIPs, there is a high administrative burden on shipping companies and ports wishing to participate in PIPs. Moreover, incentives for ships are generally provided through port revenue or public funds, so the 'polluter pays' principle is not applicable. In response to these barriers, Masodzadeh et al. (2024b) recommend implementing a global PIP focused solely on CO_2 reduction which can serve as a rebate mechanism for the future carbon pricing mechanism. They argue that, through this approach, the level of financial incentive offered to ships could be increased and perceived as truly incentivising. Furthermore, as the financial source would be an IMO GHG Fund, the 'polluter pays' principle would be incorporated. The proposed rebate mechanism can boost the motivational effect of the future carbon pricing mechanism, thereby enhancing its impact on decarbonization (Masodzadeh et al., 2024b).

Financial support for vessels' retrofit and fleet renewal

According to OECD/ITF (2022), in order to encourage the use of zero or near-zero GHG emission fuels, it may not be sufficient only to bridge the price gap between fossil based and zero or near-zero GHG emission fuels. Due to the fact that shipping companies will have to incur costs associated with switching fuels (retrofit costs), OECD/ITF (2022) suggests that zero or near-zero emission fuels may even be less costly than conventional fuels. It may be necessary for shipping companies to retrofit or replace their fleets in order to accommodate some new fuels. As far as retrofitting is concerned, the costs of such renovations could be distributed over a number of years and the investment in a new ship typically implies a reduction in operating costs through improved energy-efficiency, but these costs will prove to be a barrier for shipping companies. Therefore, OECD/ITF (2022) emphasize that one of the most important possibilities for carbon revenue recycling would be to provide financial support for retrofitting ships to become zero-emission vessels.

Developing countries account for a significant portion of the shipping industry in terms of ship ownership, ship registration and shipbuilding. 78.5% of the global merchant fleet is registered under the flag of developing countries and 38.9% of the global merchant fleet is owned by developing countries (UNCTADstat 2022a; UNCTADstat 2022b, as cited in Dominioni et al., 2023). Additionally, developing countries have high capacity in the shipbuilding sector. They built 46.8% of merchant ships of 100 GT and above in 2021 (UNCTADstat 2022c, as cited in Dominioni et al., 2023). As a result, one possible in-sector revenue expenditure option could be the financing of fleet upgrades and renewals in some developing states (Dominioni et al., 2023).

It has been asserted in some literature that shipowners may be able to manage investment risks associated with onboard technologies and ship operations. However, many shipowners have expressed a reluctance to invest in a certain type of vessel until it is clear what the dominant zero or near-zero GHG emission fuel will be in 10 or 30 years. As a result, there will be cascading effects on equipment supply chains associated with each of these fuels (Englert et al., 2021). In this regard, it may be possible to create confidence among shipowners by directing a portion of carbon revenues towards ship retrofit and fleet renewal.

Support for alternative fuel production

The literature review highlights that there is a very high global potential for alternative fuel production due to the pathways already planned in developed countries and the promise of untapped potential in developing states. Englert et al. (2021) argue that many countries, including developing countries (e.g. Brazil, India, Malaysia and Mauritius), are well positioned to become future energy suppliers. These countries tend to possess many of the natural resources needed to produce zero or near-zero GHG emission fuels, in addition to favourable access to a large volume of shipping activity.

The aim of this section is to review relevant literature to provide an assessment with an estimate of the price of alternative energy production cost for the timeline of 2030, 2040, and 2050 and compare them with the carbon revenue in the same timeline to provide a very general overview of financial balance in the process of energy transition.

Zero or near-zero GHG emission fuels' production costs could be estimated in two ways: first, in line with checkpoints of the revised IMO GHG Strategy and based on a specific fuel-equivalent energy cost (e.g. methanol equivalent energy demand and cost), and second, based on the predicted energy mix. In this vein, we need a prediction of fuel costs in the 2050 horizon that is collected from different sources, shown in table 26.

Table 26. Alternative fuel and energy prices

Fuel cost/abatement cost (CCUS)		2030	2040[5]	2050
Bio-oils ($/GJ) [1]		27	25	23
Fossil Methanol	$/GJ [2]	37.5	27.5	17.4
	$/Tonne [2,6]	746	547	346
Fossil Ammonia	$/GJ [2]	35.4	24.7	13.9
	$/Tonne [2,6]	658	459	258
Green H2	$/GJ [3]	30.5 (2019)	24.4	18.3
	$/Tonne [3,6]	3,696	2,928	2,196
Green electricity ($/GJ) [7]		8.9	7.6	6.7
LSFO	$/GJ [4,6]	16.8	16.8	16.8

	$/Tonne [4]	681	681	681
Onshore CCUS ($/t$CO_2$ abated) [2]		80	60	40

Notes:

[1]: Mærsk Mc-Kinney Møller Center for Zero Carbon, 2021: by considering the effects of a flat levy of $230/t$CO_2$eq

[2]: DNV, 2023a: cost is provided in max and min range; therefore, the max is considered for 2030 and min for 2050

[3]: IRENA, 2021: $66-154/MWh for 2019 & $32-100/MWh for 2050 (here, the average has been considered per GJ)

[4]: Ship & Bunker, n.d.: 2023 global average bunker price for VLSFO: $681 ~ $16.8/GJ (a constant price till 2050 is considered)

[5]: Fuel costs in 2040 are the average values in 2030 and 2050 (except for green electricity)

[6]: LCV for Methanol: 0.0199 (MJ/gr); for Ammonia: 0.0186 (MJ/gr); for Hydrogen: 0.12 (MJ/gr); and for LSFO: 0.0405 (MJ/gr) (source: class NK (2023) based on FuelEU maritime regulations)

[7]: DNV, 2023b: the cost of renewable electricity is considered the mean value of world average levelized cost of electricity production by solar PV and onshore wind (Table 27)

Table 27. Renewable Electricity costs

	Onshore wind ($/MWh)	Solar PV ($/MWh)	Average ($/MWh)	Average ($/GJ)
2030	34	30	32	8.9
2040	30	25	27.5	7.6
2050	27	21	24	6.7

For simplification of calculations, it is assumed that the increases in CO_2 emissions due to growth in global trade are roughly equal to the CO_2 reduction due to improved energy efficiency of vessels and improved logistic and supply chain due to for example digitalization. Referring to table 28, the steady state of energy demand till 2050 can confirm the validity of this assumption.

Table 28. Energy demand projections in IEA NZE scenario. Source: IEA, 2023

Year	2010	2021	2022	2030	2035	2040	2050
Energy demand (EJ)	10	11	11	11	10	10	10

a) Specific fuel equivalent methodology:

In this method, as shown in table 29, the yearly cost of alternative fuel production is estimated based on only one source of green fuels, for instance methanol and ammonia.

Table 29. Yearly alternative fuel production costs in 2030-2050 period based on one specific fuel scenario

	2030: 20% green energy share		**2040**: 70% green energy share		**2050**: 100% green energy share	
	1.9 EJ equivalent	Energy cost	6.65 EJ equivalent	Energy cost	9.5 EJ equivalent	Energy cost
Fossil Methanol	95.5 million ton	71.25 b$	334.2 million ton	182.9 b$	477.4 million ton	165.3 b$
Fossil Ammonia	102.2 million ton	67.26 b$	357.5 million ton	164.3 b$	510.8 million ton	132.1 b$

Notes:

- HFO LCV= 40500 KJ/KG & HFO carbon emission factor=3.114ton CO_2 per ton HFO
- LCV for Methanol: 0.0199 (MJ/gr) and for Ammonia: 0.0186 (MJ/gr) (source: class NK (2023) based on FeulEU maritime regulations)
- 2008: 731 million tonnes CO_2-eq ≈ 234.75 million tonnes HFO-eq ≈ 9.5 EJ

  (Reductions in 2030 and 2040 must be calculated based on this benchmark)
- 2030: alternative fuel requirement= 20% of 9.5 EJ= 1.9 EJ
- 2040: alternative fuel requirement= 70% of 9.5 EJ= 6.65 EJ

b) Fuel/energy mix methodology

This method considers a predicted fuel/energy mix for the period 2030-2050. Based on several scenarios considered by different institutions, some fuel/energy mixes have been predicted. As shown in table 30, the fuel/energy mix recommended by the IEA (2023) has been taken into account.

Table 30. Yearly alternative fuel production costs in 2030-2050 period based on fuel/energy mix scenario

	2030			2040			2050		
	%	11 EJ	Cost	%	10 EJ	Cost	%	10 EJ	Cost
Biofuels	8%	0.88	23.76 b$	18%	1.8	45 b$	19%	1.9	43.7 b$
Hydrogen	4%	0.44	13.42 b$	10.5%	1.05	25.62 b$	19%	1.9	34.77 b$
Ammonia	6%	0.66	23.36 b$	25.5%	2.55	62.99 b$	44%	4.4	61.16 b$
Methanol	1%	0.11	4.12 b$	2%	0.2	5.5 b$	3%	0.3	5.22 b$
Electricity	1%	0.11	0.98 b$	2%	0.2	1.52 b$	4%	0.4	2.68 b$
Fossil fuels	80%	8.8		30% / 12%	3 / 1.2[1]	Abatement cost 5.54 b$ and fossil fuel cost 10.8 b$*	11%	1.1[2]	Abatement cost 3.38 b$ and fossil fuel cost 9.9 b$*
Total cost of green and blue fuels			65.64 b$			156.97 b$			160.81 b$

Energy cost in 2050 with no decarbonization, and fully based on VLSFO (247 mil. ton & $681 per ton)			168.2 b$
	20% greening of energy demand by alternative source of energy.	70% greening of energy demand by alternative source of energy and abatement technology like CCUS to produce blue fuels from fossil fuels	100% greening of energy demand by alternative source of energy and abatement technology like CCUS to produce blue fuels from fossil fuels

Note:

- Fuel/energy mix percentages from IEA (2023)
- [1]: 1.2 EJ ≈ 92.3 million tonnes CO_2-eq (which is abated through CCUS for $60/ ton CO_2)
- [2]: 1.1 EJ ≈ 84.6 million tonnes CO_2-eq (which is abated through CCUS for $40/ ton CO_2)
- *Assumption: LNG with the price of 9 $/GJ (cheap fossil fuel, unaffected by carbon pricing) (Mærsk Mc-Kinney Møller Center for Zero Carbon, 2021) is considered for production of blue fuels through the CCUS mechanism.
- Brown cells are fossil fuels and blue cells are blue fuels. At 2040, the share of fossil fuels is 42% out of which 12% is converted to blue fuels. At 2050, the share of fossil fuels is reduced to 11% that all of them is converted to blue fuels.

Referring to table 29, it could be observed that in 2050 the price gap between conventional and alternative sources of energy has been bridged consistently with net zero decarbonization results. The only guarantee we need in this regard is the availability of green fuels at the quantity and prices predicted in the above-mentioned references. Here, the carbon price mechanism plays a crucial role in materializing these predictions, pushing shipowners, and supporting a smooth energy transition.

Alternative fuel (energy) production cost

<u>2030</u>

80% fossil fuel + 20% green fuel ≈ 8.8 EJ fossil fuel + 2.2 EJ green fuel

Price of 2.2 EJ equivalent green fuel= 65.64 b$

Price of 2.2 EJ equivalent fossil fuel (VLSFO) = $2.2 * 16.8 * 10^9$= 36.96 b$

Therefore, cost for 20% decarbonization by fuel change = 65.64 - 36.96= 28.68 b$

2.2 EJ ≈ 54.3 million ton VLSFO ≈ 169.2-million-tonne CO_2

Decarbonization cost in 2030= 28.68 b$ / 169.2 million tonne CO_2 = $170/tonne CO_2

This cost may be compensated by the tax over the remaining 80% fossil fuel:

8.8 EJ ≈ 217.28 mil. ton VLSFO → $217.28 * 10^6 * \text{tax} = 28.68 * 10^9$ $

Therefore, tax = $132/tonne VLSFO or tax = 132/3.114= $42.4/tonne CO_2

Comparatively to our calculations ($42.4/ton CO_2), Japan's feebate proposal (Japan, 2021) indicates that, between 2025 and 2030, a feebate of $56 per tonne of CO_2 will close the price gap between low-sulphur fuel oil and zero or near-zero GHG emission fuels, leading to a 17% deployment of zero or near-zero GHG emission fuels by 2030.

To understand what percentage of revenue can support the production of green fuels, it would be beneficial to calculate the cost of switching to green fuel. For instance, if the carbon tax is decided at $250/tonne CO_2, then we can realize that around one sixth ($42.4/tonne CO_2) of the revenue may be recycled in the form of investment in green fuel production in 2030. However, we can keep in mind that this level of tax is just enough to compensate for the green fuel production cost. The other costs such as green fuel distribution and supply chain cost and ship retrofit cost may be considered as well in determining the final level of tax. Ship retrofit itself imposes a very high capital cost on shipowners, including retrofit of engine, ancillary systems and special material for storage tanks (e.g. anticorrosive steel for ammonia). Additionally, operational costs for fuel storage (e.g. cooling for hydrogen and LNG) and loss in ship loading space need to be accounted for.

<u>2040</u>

30% fossil fuel + 70% green fuel ≈ 3 EJ fossil fuel + 7 EJ green fuel

Price of 7 EJ equivalent green fuel= 156.97 b$

Price of 7 EJ equivalent fossil fuel (VLSFO) = $7 * 16.8 * 10^9$= 117.6 b$

Therefore, cost for 70% decarbonization by fuel change = 156.97 - 117.6 = 39.37 b$

7 EJ ≈ 172.84 million tonne VLSFO ≈ 538.2 million tonne CO_2

Decarbonization cost in 2040= 39.37 b$ / 538.2 million tonne CO_2 = $73/tonne CO_2

Now, this cost may be compensated by the tax over the remaining 30% fossil fuel:

3 EJ ≈ 74.07 mil. tonne VLSFO → $74.07 * 10^6 * \text{tax} = 39.37 * 10^9$ $

Therefore, tax = $531/tonne VLSFO or tax = 531/3.114= $170.7/tonne CO_2

The comparison of green fuel production cost in 2030 and 2040 indicates that, despite technology advancement and reduction in decarbonization cost per tonne of CO_2 (from $170 to $73), an increase in overall decarbonization cost is foreseen (from 28.68 b$ to 39.37 b$), due to higher decarbonization (from 20% to 70%). If we assume a flat tax rate of $250/tonne CO_2, then the yearly share of revenue recycling for green fuel production is raised from 17% in 2030 to 68% in 2040. Therefore, the revenue distribution cannot work on a yearly-based mechanism, instead through efficient planning and organization it could be a cumulative scheme to save the taxes in starting years for expenditure in the further phases of decarbonization. In the same direction, the Mærsk Mc Kinney Møller Center for Zero Carbon Shipping (2021), through a cumulative income and cumulative cost method and based on a flat levy scheme of $230/t CO_2 eq, has predicted $1.8 trillion in 2050 (Figure 56).

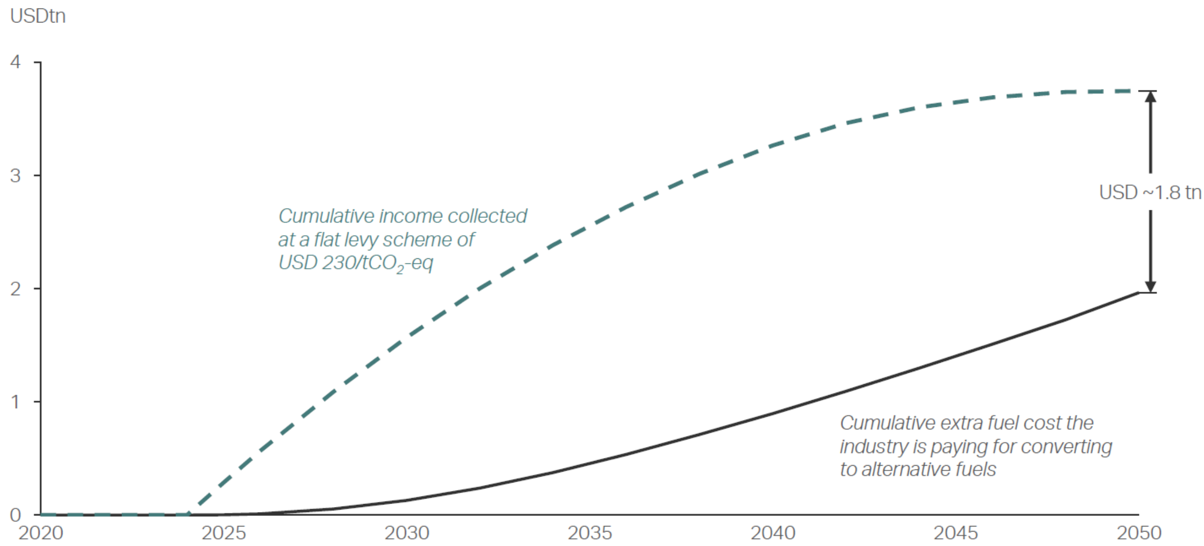


Figure 56. Cumulative income and cumulative alternative fuel cost calculations. Source: Mærsk Mc Kinney Møller Center for Zero Carbon Shipping, 2021

Enhancement of maritime transport energy infrastructure and services

One method of in-sector distribution of carbon revenue is through projects which support the development of port infrastructure that accelerates the uptake of zero or near-zero GHG emission fuels (OECD/ITF, 2022; ICS and Intercargo, 2021). There is considerable variation in the number and capacity of ports among coastal countries. In some coastal States, there may be limited opportunities for port infrastructure enhancements. In some developing countries, there are numerous ports which are of significant size. However, in many others, including some SIDS and LDCs, there are very few ports, and many of them are relatively small. As a result, part of carbon revenue could be used to improve port infrastructure as well as to increase their efficiency, effectiveness and performance. For instance, many SIDS would greatly benefit from improvements in dock loading facilities, additional storage and warehousing space, and segregated cargo and passenger areas (Adeoti et al., 2020, as cited by Dominioni et al., 2023; UNCTAD, 2022). It is also possible to recycle some of the revenue to adapt mitigation measures to protect ports in SIDS exposed to natural disasters (Van Houtven et al., 2022, as cited by Dominioni et al., 2023).

A direct relationship exists between port performance and shipping costs and overall shipping emissions. The improvement of port performance through the use of digital technology or advanced cargo-handling equipment may result in reduced turnaround times and waiting times at ports, thereby reducing maritime transportation costs and CO_2 emissions. Additionally, by adapting alternative fuel infrastructure, ports can become major players in the energy supply chain, catering not only to the shipping industry, but also to other sectors. According to Rojon et al. (2021), SIDS and LDCs experience higher transport costs than the world average and this could worsen with the implementation of additional IMO climate policy measures. Therefore, Rojon et al. (2021) recommend investments in infrastructure as a viable means of addressing the negative impacts of such regulatory measures. If there is a viable business and development case, new ports could also be financed in these countries (Dominioni et al., 2023).

It would be possible for an IMO GHG Fund to support financially technology providers, for example by providing subsidized insurance coverage for pilot projects. A similar financial support could facilitate the type-approval process for new technologies and green fuels (a contract between technology providers and classification societies).

Additionally, an IMO GHG Fund and/or relevant financial mechanisms could provide support to players in the energy supply chain. The support may take the form of financial assistance to facilitate the establishment of joint ventures between ports, rail/road operators and fuel producers, for example. Similarly, green bonds and loans could facilitate the emergence of innovative business models between different stakeholders, such as the Maritime Energy Contracting (MEC) model and the Energy Supply Contracting (ESC) model.

Capacity building, education and training

A recent DNV report emphasises decarbonization and digitalization as two dominant trends in maritime transformation, as well as the skills that seafarers need to cope with these changes (DNV, 2023c). This report reveals a significant skills gap in handling zero or near-zero GHG emission fuels. Similarly, Ölçer et al. (2023) have suggested that the major skill gaps are the ability to handle zero or near-zero GHG emission fuels and the proficiency to maintain and operate advanced and electrified propulsion systems. Therefore, regular skill upgrades and refresher courses throughout a seafarer's career are essential to remain up to date with the latest environmental technologies and regulations. There is still uncertainty regarding the dominant fuel option of the future, as well as the regulatory environment. As a result, planning for the transition of the maritime workforce and attracting investments towards new skills programmes is challenging in this environment (ITF/ICS/LR, 2022). However, 'no matter which fuel or fuels are ultimately favoured, transitioning to a decarbonized shipping industry will require additional training to at least hundreds of thousands of seafarers up to 2050' (ITF/ICS/LR, 2022).

On the other hand, developing new training courses can be costly and can be undertaken in response to specific regulatory or industry requirements (DNV, 2023c). Due to a lack of funding and resources, it is difficult for maritime education and training institutes (METI) to maintain and upgrade their equipment and facilities. An ambitious decarbonization goal for shipping is necessary to unlock the investments required to reskill and train the maritime workforce (ITF/ICS/LR, 2022). This prerequisite has now been met by a consensus on reaching net-zero GHG emissions from international shipping by or around 2050 (IMO, 2023b). As a result, carbon pricing debates have been resumed seriously, and a major consideration is the distribution of carbon pricing revenue (Dominioni and Englert, 2022). A recommendation is that a small portion of a GHG Fund can be devoted to training and upskilling the maritime workforce. Investments could be made through, for instance, Maritime Education and Training Institutions (METIs) and Maritime Technology Cooperation Centres (MTCCs) to modernise or renovate training infrastructure, train the trainers and provide subsidized courses for seafarers. In addition, with such financial support, METIs and MTCCs could collaborate with technology providers to deliver refresher and specialised courses. The other option could be supporting the shipowners financially to provide computer-based training (CBT) on board their vessels. Furthermore, port technicians engaged in alternative fuel bunkering infrastructure and electrification apparatuses, such as battery chargers and onshore power supply equipment, may benefit from these financial supports for updating their knowledge and skills. In order to keep abreast of the latest technological advancements and regulations, even PSC officers at the frontline of policy execution could receive refresher courses.

With reference to the recommendations for carbon revenue recycling in the proposals to the IMO, shown in table 31, we can see there is no explicit distinction between in-sector and out-of-sector distribution of carbon revenues and, at the time of this literature review, the comprehensive assessment would model the following seven proposed areas for revenue disbursement to assess potential impacts on States and the fleet: RD&D Capacity-building and negative impact mitigation; Address DNI as appropriate; Reward for eligible fuels, General GHG mitigation and adaptation; Equitable transition; and Administration. For instance, it has been empirically observed in the candidate proposals that there is no clear border between maritime and non-maritime sectors when these proposals recommend supporting R&DI, technical cooperation, or capacity building.

Table 31. Revenue use in carbon pricing proposals submitted to IMO

Proposal	Main spending categories	Administered by
GHG Levy (Marshall Islands and Solomon Islands, 2021)	Climate change adaptation/mitigation (at least 51%), Administrative costs (16%),Research development and deployment (up to 33%)	Green Climate Fund International Maritime Research and Development Board (to be established)
Levy (ICS & Intercargo, 2021)	Research and development, new bunkering infrastructure, assist maritime GHG reduction of developing countries	IMO Climate Fund (to be established)
Feebate (Japan, 2021)	Incentives for first movers, technical co-operation, carbon offset credits	IMO's Integrated Technical Cooperation Programme2
Funding and reward system (Argentina et al., 2022)	Rewards to ships with emissions below benchmark (40%), Capacity building (30%), Research development and deployment (20%), Administration costs (10%)	An International Maritime Sustainability Funding and Reward Board (to be established) within the IMO structure
Cap and trade (Norway, 2022)	Address disproportionate impacts on states, uptake of zero or near-zero GHG emission fuels, production of zero-emission fuels, infrastructure, R&D	Green Climate Fund
International Maritime Sustainable Fuels and Fund (F&F) mechanism proposed by China (IMO, 2023e) as cited in (IMO, 2023d)	1. [50%] would be used for in-sector capacity building and negative impact mitigation in developing countries, including the construction of infrastructure for alternative marine fuels and funding, inter alia, e.g., for the IMO GHG-Trust Fund, to support other maritime GHG reduction projects in developing countries 2. [45%] would be used for R&D programmes and technology transfer, including	Not clearly mentioned. Probably same as (Argentina et al., 2022): An International Maritime Sustainability Funding Board

	addressing the intellectual property issues to make the innovative fuels/technologies accessible for developing countries and having them join the production of new fuels.	
Combination of the GHG Fuel Standard with a levy (fact sheet by Denmark, 2023) (IMO, 2023f)	Investment in RD&D, production of the new fuels, deployment of infrastructure linked to those fuels, mitigation of negative impacts on fleets, with a particular focus on most affected states, and particularly SIDS and LDCs.	Not clearly mentioned
International Maritime Sustainability Funding and Reward (IMSF&R) system (fact sheet by Brazil, 2023; IMO, 2023g)	Fuels consumed to serve the ports of developing countries likely to be negatively impacted would obtain [5%] more allowance of carbon emissions, which is equivalent to lowering the fuel costs for these specific voyages and so as the freight rate. [30%] of the funding contributions would be used to support capacity building and negative impact mitigation in developing countries. [20%] of the funding contributions would be used to finance the RD&D programmes and technology transfer, which would provide additional opportunities for developing countries to freely access innovative technologies/fuels.	An International Maritime Sustainability Funding and Reward Board

3.4.2.3.2 Out-of-sector distribution

According to Dominioni and Englert (2022) and Dominioni (2023), from the perspective of general climate mitigation or adaptation, in some cases out-of-sector spending of carbon pricing revenues might be more effective. International shipping does not necessarily represent the most cost-effective opportunity for climate change action (Dominioni & Englert, 2022). In addition, the recycling of carbon revenues into non-shipping-related activities can provide financial support to countries with limited opportunities for in-sector projects (for example, those lacking the capability to produce zero or near-zero GHG emission bunker fuels). This approach enables carbon pricing to be implemented in a more equitable and politically feasible manner (OECD/ITF, 2022). Two mechanisms for the out-of-sector distribution of carbon revenues were identified in the literature review. First, development of an instrument in response to the principle of "common but differentiated capabilities and respective capabilities" (CBDR&RC) (e.g. Aidun et al., 2021; Parry et al., 2018; Wemaëre et al., 2023), and second, capacity building and technology transfer to SIDS and LDCs (e.g. Dominioni et al., 2023).

Development of an instrument in response to the CBDR&RC principle

During the past decade, there has been a contentious debate within IMO on whether the CBDR&RC principle should be applied to IMO instruments which has obviously delayed the discussion on carbon pricing mechanisms within IMO (Wemaëre et al., 2023). According to Wemaëre et al. (2023) and Dominioni (2023), the Initial IMO Strategy (three years after the Paris Agreement) also emphasized the need for any measure to be cognizant of the CBDR&RC principles enshrined within the UNFCCC which will also guide the Paris Agreement in light of national circumstances. Nevertheless, in contrast to the NMFT principle, CBDR&RC is not recognized by any IMO treaty (Wemaëre et al., 2023). According to Aidun et al. (2021), while developed countries argued that CBDR&RC conflicts with the principle of NMFT, the IMO Secretariat took the position that the two principles do not conflict because CBDR&RC applies to countries while NMFT applies to ships. According to Wemaëre et al. (2023), a carbon pricing mechanism may be applied uniformly to all ships in accordance with IMO's NMFT principle, and may initiate a differentiated redistribution of carbon revenues following the CBDR&RC principle to avoid "disproportionately negative impacts" (DNI). It is evident that SIDS and LDCs are most vulnerable to the economic impacts of decarbonization (Rojon et al., 2021; OECD/ITF, 2022; Dominioni, 2023; Wemaëre et al., 2023), as well as to the physical effects of climate change (Englert et al., 2021; Nuttall et al., 2021; Wemaëre et al., 2023). As a result, an equitable transition can be achieved by addressing DNI effectively and objectively, for example by channelling a portion of the revenues in priority to countries that are particularly vulnerable due to their socioeconomic conditions and the fact that shipping costs will be higher for these countries (e.g. Parry et al., 2018; Aidun et al., 2021; Wemaëre et al., 2023).

According to the World Bank (2023), providing carbon revenues to developing countries, LDCs and SIDS may help closing the financing gap between current climate finance flows and their climate finance needs. Many developing countries, including some LDCs, have limited or no opportunities to make significant investments in maritime transport infrastructure and services. In this regard, LLDCs are a clear example since they lack direct access to the sea and are often situated far from any coastline. It is noteworthy that more than one-third of LDCs

(17 out of 46) are also LLDCs (Dominioni et al., 2023). According to the World Bank (2023), limiting carbon revenue recycling to maritime transport-related countries could deprive LLDCs of financial support, which would undermine the objective of supporting a more equitable transition.

Aidun et al. (2021) state that "CBDR&RC is widely recognized in international law, and although it has not always prevailed at the IMO, it is expressly incorporated into the IMO's Initial GHG Strategy". They also argue that the concept of CBDR&RC can influence the way the carbon pricing is implemented and add that "some have argued that a carbon-pricing scheme to reduce international shipping emissions should include a fund that allocates money to developing countries in order to respect CBDR&RC" (Aidun et al., 2021).

There are also some carbon pricing proposals that seem to adhere to the CBDR principle. For instance, the CBDR principle is the cornerstone of a rebate mechanism proposal submitted by the International Union for Conservation of Nature (IUCN) in 2010 (IMO, 2010b). According to IUCN, "the amount of rebate would be calculated annually in a proportion to a key. The proposed key is a country's share of global imports by value" (IMO, 2010b). According to the Marshall Islands and Solomon Islands proposal, instead of exempting shipping routes from carbon pricing for countries facing potentially disproportionately negative impacts, the revenues from carbon pricing will compensate these countries more effectively than exemptions (Marshall Islands and Solomon Islands, 2021 as cited in OECD/ITF, 2022). Argentina et al. suggest that the benchmark levels that contribute significantly to the reward system can be adjusted for ships that have "served one or more ports of developing countries likely to be negatively impacted" (Argentina et al., 2022, as cited in OECD/ITF, 2022). In this way, they introduce a differentiated approach to carbon pricing to address the CBDR&RC principle.

Capacity building and technology transfer to SIDS and LDCs

In Article 9 of the Paris Agreement, it is acknowledged that international climate finance plays an important role in the development of capacity in SIDS (OECD, 2023). According to OECD (2023) "capacity development is among the most complex areas of international development practice, and developing capacity in SIDS is even more complex given their specific circumstances". In this direction, OECD's Development Assistance Committee (DAC) develops and improves policies and programmes to address SIDS' particular needs, and works with them to address obstacles they encounter in accessing and absorbing finance for resilient and sustainable development (OECD, 2023). In SIDS, the energy transition is more challenging due to the lack of necessary technologies, financing, capacity and physical space in some cases to deploy renewable sources of energy such as solar panels (OECD, 2023). According to the International Solar Alliance (2023), the following policy, technological and financial barriers hinder the development of solar energy infrastructure in SIDS and LDCs:

- Policy (regulatory) barriers including: changes in regulations, lack of energy policy and planning, unclear grid regulation, procurement risks, lack of clear procedures, land risks (e.g. lack of spatial planning and site selection) and lack of institutional capacity.
- Technological barriers including: lack of access to information and data, lack of technical capacities, unfit infrastructures and project execution risks.
- Financing barriers including: lack of access to information and data, currency risks, lack of financial guarantees and payment risks.

According to OECD/ITF (2022), there can be a substantial portion of carbon pricing revenues reserved for climate-mitigation and adaptation projects in SIDS and LDCs. Additionally, financial support can empower universities and research institutes in SIDS so they can develop expertise in relevant areas and foster exchange of practices among academics (OECD, 2023). According to Japan's proposal, one of the main spending categories is technical co-operation through IMO's Integrated Technical Cooperation Programme. Similarly, capacity building is also a major spending category in the Argentina et al. proposal (OECD/ITF, 2022). According to World Bank (2021), carbon revenues could be redirected into technical projects for the production of renewable energy in developing countries. There is considerable potential in this sector for the production of zero or near-zero GHG emission fuels (World Bank, 2021) that could be used in green ships. Therefore, investment in out-of-sector activities will have a positive impact on decarbonization activities within the sector.

3.4.2.4 Distribution framework

In general, the literature review on this matter found that international shipping could consider two ways to manage revenues from a maritime GHG emissions pricing mechanism. The first is passive carbon revenue, such as feebate schemes, in which revenues are distributed according to predetermined rules which do not leave any discretion to the implementing entity. By contrast, in active management of carbon revenues, projects and programmes are selected and financed through a competitive bidding process to a fund. Under such a process, project proposals are submitted and assessed according to the policies and criteria of the fund. This is a common approach adopted in climate finance as the process helps in selecting projects and programmes that are expected to align more closely with the expectations of the fund (Dominioni et al., 2023).

There may be a need for an international institution or mechanism to allocate and distribute carbon pricing revenues. In this regard, Dominioni and Englert (2022) argue that this mechanism could be established under the auspices of IMO or another UN organization. An example of this could be the Green Climate Fund under the auspices of the UNFCCC. IUCN also argues that the disbursement of the revenue could be managed by the operating entity of the financial mechanism of the UNFCCC (IMO, 2010b).

The World Bank (2023) argues that "a revenue distribution framework built around three levers and three funding windows can effectively deliver climate and equity benefits for countries". The World Bank (2023) identifies three levers (recipients' lever, use lever, and financing terms lever) that determine which countries can access which funding window, for what carbon revenue use and under what financing terms. Detailed access modalities and project or programme selection criteria may also be considered in further analyses.

The recipient lever defines which groups of countries (1. SIDS and LDCs; 2. All other developing countries; 3. Developed countries) could access each funding window of carbon revenues. The use lever defines how carbon revenues in each share could be spent among the revenue use options most aligned with the IMO GHG Strategy, selected principles and desirable features. The financing terms lever defines what financing conditions may apply to each group of countries when they access carbon revenues (figure 57).

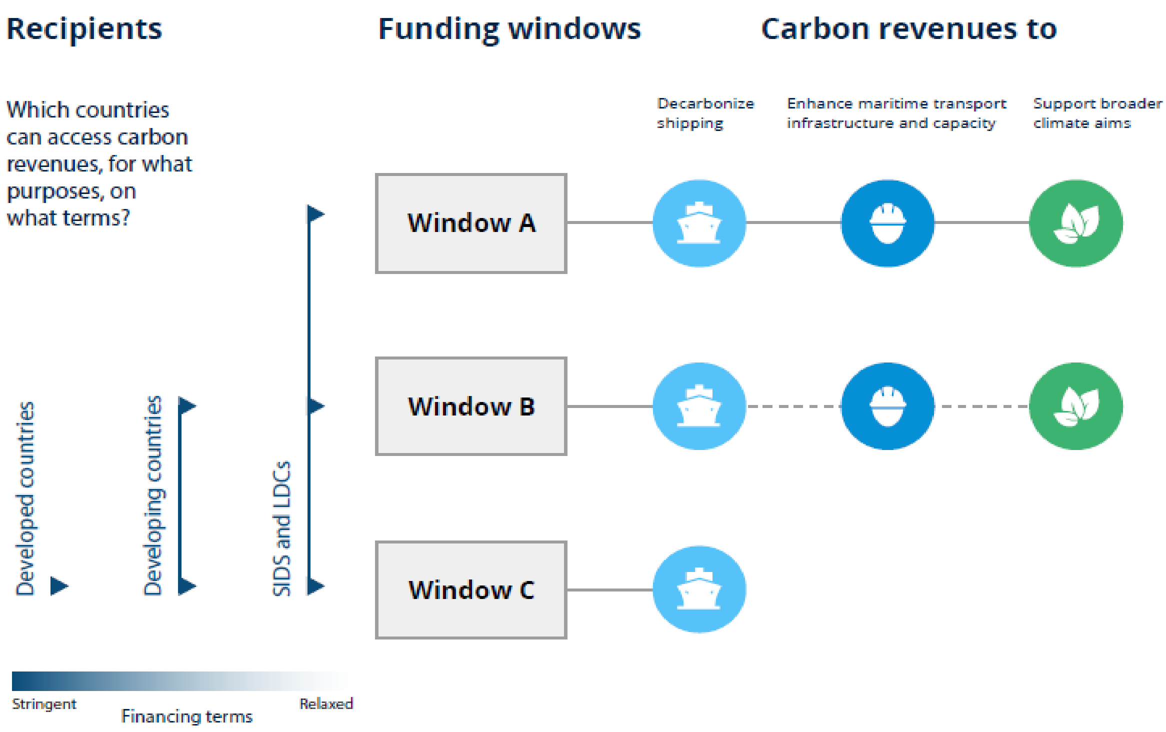


Figure 57. Carbon revenue distribution framework for international shipping. Source: Dominioni et al., 2023

As shown in figure 57, carbon revenues could be accessed via three dedicated funding windows. Window A could be reserved for SIDS and LDCs, however, it could also be opened to other developing countries based on, for instance, climate vulnerability criteria. The fundings accessible through window A could be spent for shipping as well as non-maritime decarbonization activities and broader climate aims. Window B could be reserved for all developing countries with primary focus on shipping decarbonization and possible other broader climate aims. Window C could be accessible to all countries with exclusive focus on shipping decarbonization.

3.4.2.5 Recipients of carbon revenues

As we can see, the World Bank approach is more about a top-down approach in recycling carbon revenue. This means the distribution framework will deal with governments rather than maritime stakeholders directly at the bottom level. The World Bank proposal has recognized the possibility of revenue recycling towards private sectors "either directly (through a feebate scheme or a fund with direct access) or indirectly (through governments as intermediaries)" (Dominioni et al., 2023). In the distribution framework proposed by the World Bank, there is no recognition of maritime stakeholders, instead governments have been placed with an intermediary role between the IMO GHG Fund and maritime stakeholders. Later in this section, it can be observed how this approach could be problematic and make a source of split incentives between governments and maritime stakeholders.

In the World Bank report, SIDS and LDCs have been given priority in accessing fundings derived from carbon revenues, followed by other developing countries, and then developed States (Dominioni et al., 2023). However, in revenue distribution between public (governments) and private (shipping stakeholders) sectors, there is no consensus in the literature. The World Bank (2023) and Dominioni (2023) are inclined toward the distribution of revenues through government channels. Dominioni (2023) argues that, while distribution through countries is easier to track, distribution to stakeholders is more challenging. In accordance with the World Bank (2023), the private sector may receive carbon revenues directly or indirectly through government programmes, either under a feebate scheme or through the process of bidding. For instance, where maritime actors have demonstrated significant actions in shipping decarbonization, the revenue could be directly recycled to them, and in SIDS and LLDCs, where the maritime stakeholders are not the main players, the carbon revenue could be recycled to their governments. This method necessitates a very detailed study about stakeholders including identification of stakeholders, their interests, their potential and their interactions. This stakeholders' analysis could be connected later with the areas where the carbon revenue could be spent (figure 58).

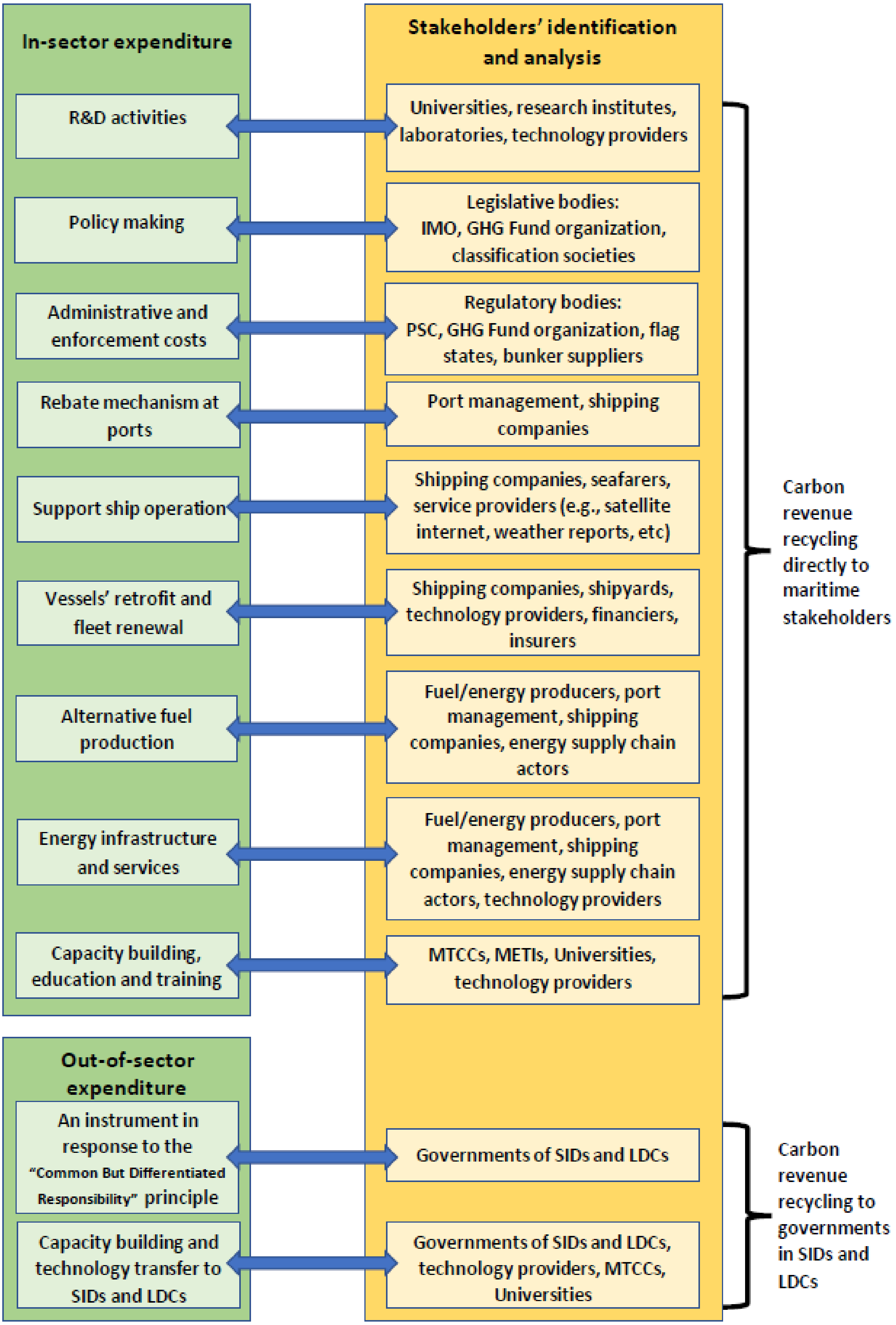


Figure 58. A mixed public-private distribution framework

Who can receive the recycled credit, shipping stakeholders, governments, or both?

As a result of the highly international nature of the shipping industry, the definition of ship ownership is complex. "The country of beneficial ownership refers to the country in which the company with the main commercial responsibility for the vessel is located" (UNCTADstat, 2022a). Taking note of this complication, Dominioni and Englert (2022) argue that direct distribution of carbon revenues to shipping companies would bypass the country of ownership while recycling carbon revenues to governments would circumvent this problem. However, this theory can lead to a source of split incentive between shipowners and governments. While shipowners have to invest in their fleet energy transition, all the recycled credits go to governments and there would not be any guarantee that shipowners can attain a deserved portion of that. According to Ciplet et al. (2022), there is a lack of data on who controls climate finance within countries once funds are distributed. They specifically emphasize the power of elites in influencing climate finance governance, what Frank (1974) called the 'lumpenbourgeoisie' which could lead to within-country inequalities.

In addition, if a shipowner belongs to a developed country and the recycled carbon revenue flows to the government of that developed country, this would not be aligned with the revenue distribution policy and, at the same time, the shipowner might be discouraged to invest majorly in the energy transition. This could be generalized to the other stakeholders as well. Shipping energy transition has significant impacts on different stakeholders such as fuel producers, fuel suppliers, technology providers, shipyards, ship owners, charterers and shipping companies.

3.4.2.6 Literature gaps

1. There is a lack of literature that addresses the overhead costs associated with shipowners, such as retrofitting and fleet renewal.
2. Literature does not explicitly describe the methodology for calculating and estimating the cost of green fuel production based on maritime demand in 2050.
3. A very limited amount of literature has been published regarding shipboard renewable energy capture, such as wind and solar energy, and their impact on the estimation of the final energy demand of shipping and fuel mixtures.
4. Fuel standards and their implementation framework are clearly lacking in the literature.

5. There has been limited research on green finance, particularly in relation to energy transition in the shipping industry.

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APPENDIX

1. Future shipping decarbonization technologies and fuels

1.1. Ammonia

Ammonia has been explored as a potential alternative fuel for the shipping industry in recent years. It is considered an emerging fuel, indicating it is still in the early stages of development. Based on data collected from various sources (i.e., (Balcombe et al., 2019; DNV, 2019a, 2019c, 2019b; The Royal Society, 2020; Xing et al., 2020; Ampah et al., 2021; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; Lloyd's Register, 2023b; Raucci et al., 2023)), ammonia has several advantages and disadvantages as summarized below:

Advantages of ammonia as a marine fuel:

- Versatility: Ammonia can be used in various combustion engines as well as fuel cells.
- Storage: Ammonia can be stored at relatively lower/higher pressure temperature than liquefied hydrogen and LNG, making it easier to handle compared to liquefied hydrogen or Natural Gas (LNG).
- Energy density: Ammonia has a higher volumetric energy density compared to hydrogen. This makes it more efficient for storage and transportation.
- Infrastructure: There is already a wide storage and delivery system for ammonia. Utilising existing infrastructure is a bonus.
- Potential for carbon neutrality: Ammonia can be produced from renewable energy sources such as wind or solar power, resulting in carbon-free ammonia.

Disadvantages of ammonia as a marine fuel:

- Safety: Ammonia is highly toxic, requiring additional safety measures and increased costs to mitigate risks. Ammonia also has poor ignition quality, toxicity and corrosiveness.
- Cost: Green ammonia production is currently expensive. In comparison to LNG, its OPEX are up to four times higher.

- Infrastructure limitations: The necessary bunkering infrastructure for ammonia is currently lacking along major cargo routes.
- GHG emissions: It emits higher levels of NO_x compared to traditional fuels. Current production methods for ammonia generate high GHG emissions (grey or blue ammonia produced from fossil fuel or mix electricity respectively). However, carbon-free pathways (production onshore and use on board ships) using renewable energy sources (through electrolysis) are being explored.

While the utilization of ammonia as a marine fuel is yet to be fully commercialized, further technological advancements, safety considerations and policy/regulatory developments are necessary. See table A for studies that addressed ammonia.

1.2. Hydrogen

Hydrogen is considered a promising alternative fuel for the shipping industry due to its potential to reduce GHG emissions. It generates less GHG emissions compared to conventional maritime fuels and yields more energy per unit mass (Al-Enazi et al., 2021). Hydrogen can be used as a future bunker fuel and may enable the complete replacement of hydrocarbon fuels in the maritime sector (Ampah et al., 2021). However, there are certain challenges that hinder the widespread utilization of hydrogen fuel. The advantages and disadvantages of hydrogen are presented below based on various studies (i.e. Balcombe et al., 2019; DNV, 2019a, 2019c, 2019b; The Royal Society, 2020; Xing et al., 2020; Ampah et al., 2021; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; Lloyd's Register, 2023b; Raucci et al., 2023).

Advantages of hydrogen as a marine fuel:

- Reduced GHG emissions compared to conventional fuels
- Potential to completely replace hydrocarbon fuels in the future (med-term)
- Enable zero-emission (with fuel-cell)
- Capable of becoming compatible with engines, turbines and burners with minor modifications
- Can be produced from electrolysis near ports

Disadvantages of hydrogen as a marine fuel:

- Higher production costs compared to conventional fuels
- Special handling requirements for storage and transportation
- Lower volumetric energy density (50% of LNG) and large storage tanks influence vessel cargo space, limiting application to short-range coastal vessels, requiring more space on board ships
- Safety concerns due to its high explosive limit. With the extensive flammability range, there are needs for extra safety mitigating measures at an added cost
- Absence of supply, bulk storage and bunkering infrastructure
- Expensive CAPEX and OPEX (around three times greater than LNG) and viable production likely decades away

Overall, hydrogen as a marine fuel is still in the research and development phase and not yet commercially used for ships. However, in a comprehensive review of studies in Bilgili (2023), it is indicated that hydrogen, along with ammonia, is expected to be the most preferable fuel in terms of socio-economic cost and has significant potential for use in the shipping industry. Also, it is projected that by 2035, hydrogen and ammonia could constitute 70% of the total market share for alternative fuels (Halim et al., 2018). See table A for studies that addressed hydrogen.

1.3. Fuel cells

Fuel cells are electrochemical devices that convert chemical energy from a fuel into electrical energy. They operate by passing the fuel, typically hydrogen, over an anode and introducing oxygen from the air to a cathode, separated by an electrolyte. The reactions that occur at the anode and cathode produce electricity, heat and water vapor as byproducts (DNV, 2019b).

Fuel cells are considered an alternative marine power source for ships, offering the potential for reduced GHG emissions. There are various types of fuel cells that can be used in marine applications, i.e. proton exchange membrane fuel cells, alkaline fuel cells and direct methanol fuel cells. Owing to the higher power demands, molten carbonate fuel cells and solid oxide fuel cells have become the main options for maritime applications. In a literature review on alternative energy sources for maritime transportation, the hydrogen fuel cells are discussed with wind power and solar energy as possible alternatives (Dolatabadi et al., 2023; Duong et al., 2023; Fan et al., 2022). There are several demonstration projects that were developed for fuel cell applications in the maritime industry, such as METHAPU, ZemShip, FellowSHIP and E4Ships (Xing et al., 2020).

Based on various studies (Balcombe et al., 2019; DNV, 2019a, 2019c, 2019b; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Maersk Mc-Kinney, 2021; Kouzelis et al., 2022; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Herdzik, 2023; Lloyd's Register, 2023b; Raucci et al., 2023) , fuel cells advantages and disadvantages are presented below.

Advantages

- Hydrogen fuel cells have the potential to significantly reduce GHG emissions in the shipping industry, contributing to environmental sustainability.
- They have the advantage of being able to utilize hydrogen, methane, and methanol as feasible fuels, making them adaptable to different fuel sources.
- Advantages of fuel cells include their high electrical efficiencies, typically up to 60%, depending on the type of fuel cell and fuel used, and even up to 85% if waste heat is captured in a cogeneration scheme (Tronstad et al., 2017). They also have lower vibration and noise emissions compared to combustion engines.

Disadvantages

- Fuel cell technology is still in its infancy for ships and further technical development is required for improved efficiency, performance and cost-effectiveness. Fuel cells have mainly been used for power plants for commercial yachts and small ferries as well as auxiliary power units for Ro-Pax or car carriers (Xing et al., 2020). The E4ships lighthouse project in Germany has made advancements in fuel cell technology for seagoing ships (DNV, 2019b).
- The cost of fuel cells is relatively high but expected to decline over time, increasing their viability as an alternative power source.

- In terms of the maturity and usage of fuel cells for marine applications, the technology is still in the early stages. Relevant technological development, feasibility analysis and pilot projects are needed to assess their applicability in the maritime industry. At present, there are no demonstration projects for full propulsion of large cargo ships because of the limited maximum power of fuel cells.
- Infrastructure and availability of bunkering for hydrogen fuel cells are important considerations for their widespread adoption in the shipping industry. Currently, the infrastructure for hydrogen bunkering is limited, but efforts are being made to expand it in key ports and routes (Tronstad et al., 2017). The development and availability of bunkering infrastructure are crucial for the adoption of hydrogen fuel cells as a viable power source.

Several studies have examined the feasibility and potential of fuel cells for maritime applications. These studies have provided insights into the technical feasibility, risk analysis and potential of fuel cells for reducing emissions in the shipping industry. Further research is needed to enhance the efficiency, performance and cost-effectiveness of fuel cells in marine applications.

Furthermore, additional technical development and improvements in efficiency, dynamic response, costs and lifetime are still needed for fuel cells to reach a degree of maturity sufficient for substituting main engines in ships (Xing et al., 2020). See table A for studies that addressed ammonia.

1.4. Biofuels

Biofuels, as an alternative marine fuel for shipping, can be divided into different types, i.e. ethanol (see the methanol section) and liquid biofuels. The liquid biofuels are derived from biomass sources such as vegetable oils, animal fats or other organic materials. Biodiesel and hydro-treated vegetable oil (HVO) are examples of liquid biofuels that can be used in marine engines (Foretich et al., 2021). See subsections on biodiesel, HVO and DME.

Based on various sources (i.e. DNV, 2019a, 2019c, 2019b; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Foretich et al., 2021; Maersk Mc-Kinney, 2021; Kouzelis et al., 2022;

MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Lloyd's Register, 2023b; Raucci et al., 2023), the advantages and disadvantages of biofuels are presented below.

Advantages of biofuels as marine fuels

- Biofuels are renewable energy sources that can help reduce GHG emissions (carbon neutral) compared to conventional fossil fuels.
- Liquid biofuels, such as biodiesel and HVO, are compatible with existing diesel engines and infrastructure without significant modifications.
- Biofuels have been tested and used in various pilot projects and research initiatives for marine engines.
- Ethanol is a cleaner-burning fuel that can reduce emissions of certain pollutants.

Disadvantages of biofuels:

- The production of biofuels may compete with food production or lead to deforestation if not sustainably sourced.
- Depending on feedstock and production methods, biofuels can have varying degrees of environmental impact and net carbon emissions.
- Cost of producing biofuels can be higher compared to conventional fossil fuels. This may limit their commercial viability.
- Availability of biofuels and supporting infrastructure, including bunkering facilities (absence of bunkering infrastructure), may be limited.
- With respect to the HVO (advanced biodiesel), the quality and consistency of production varies, there is lack of agreed fuel standards including its high NO_x and particulate matter emissions.
- The use of biofuels as an alternative marine fuel is still in the early stages on a global scale.

Various studies have examined the prospects and challenges of alternative marine fuels, including biofuels, for sustainable maritime decarbonization (Ampah et al., 2021; Bilgili, 2023). The viability of biofuels as a shipping fuel has been assessed based on technical, environmental, and economic factors (Foretich et al., 2021). See table A for studies that addressed biofuels.

1.4.1. Dimethyl ether

Dimethyl ether (DME) is considered as an alternative marine fuel for shipping. It falls under the category of alternative fuels that have the potential to reduce the environmental impact of conventional fossil fuels used in the maritime sector (Bilgili, 2023). Dimethyl ether is primarily produced from natural gas derived from biomass through gasification. It can also be produced from coal or methanol. Various studies have examined the potential of DME as an alternative marine fuel. These studies evaluate its properties, compatibility with existing engines and infrastructure, and the environmental impact of its usage (Kegl et al., 2021). Bellow are advantages and disadvantages of DME (Bilgili, 2023).

Advantages of DME as a marine fuel:

- Properties: DME has several characteristics that make it a viable fuel option. It is a clean-burning fuel with low emissions of particulate matter, sulphur and NO_x. DME is also non-toxic, biodegradable, and has a high cetane number, which contributes to its efficient combustion.
- DME has the advantage of lower emissions compared to conventional fossil fuels. It has the potential to reduce GHG emissions and contribute to the decarbonization of the maritime sector. However, further research is needed to assess the full life cycle environmental impact of DME, including its production and transportation.

Disadvantages

- The cost of DME production and infrastructure development is a significant consideration for its widespread adoption. Currently, the cost of DME as a marine fuel is higher compared to conventional fuels. However, with advancements in technology and economies of scale, the cost could potentially decrease in the future.

- DME has been used as a fuel in various applications, including power generation, heating and transportation. However, its use as a marine fuel is still at an early stage of development and requires further research and evaluation.
- The availability of DME as a marine fuel is currently limited, and the bunkering infrastructure for DME is not well-established. Further development and investment in infrastructure are required to support the widespread use of DME as a marine fuel.

See table A for studies that addressed DME.

1.4.2. Biodiesel

Biodiesel is a type of biofuel that is considered as an alternative marine fuel for shipping. It is derived from various feedstocks such as soybean oil, palm oil, sunflower oils and waste cooking oil (Ampah et al., 2021). Biodiesel is miscible with petroleum-derived products, thus can be blended with traditional marine oils in any ratio and combusted in marine engines without requiring major changes to the engine hardware. It has superior fuel properties compared to traditional marine fuels. It can be used as an additive or a replacement for marine diesel oil (MDO) and marine gas oil (MGO) in low to medium speed diesel engines (Ampah et al., 2021). Different types of biodiesels exist, i.e. soybean oil biodiesel, palm oil biodiesel, sunflower oil biodiesel and waste cooking oil biodiesel.

Based on data retrieved from various sources, (e.g. DNV, 2019c, 2019a, 2019b; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Foretich et al., 2021; Maersk Mc-Kinney, 2021; Kouzelis et al., 2022; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Lloyd's Register, 2023b; Raucci et al., 2023), advantages and disadvantages of biodiesel are explained below.

Advantages of biodiesel as an alternative marine fuel:

- Biodiesel has the potential to decrease pollutant emissions when combusted directly or blended with marine fuels.

- Biodiesel has superior fuel properties compared to traditional marine fuels, which can lead to improved performance and combustion characteristics.
- It can be blended with existing marine oils and can be used with current engine technologies without major modifications.
- Biodiesel presents an opportunity for the development of a domestic bioeconomy, promoting regional job creation and economic growth.
- Biodiesel has been tested in marine engines since 1998 and large engine manufacturing companies have conducted research and testing of biodiesel in their engines.
- It provides a near-term potential for meeting IMO fuel sulphur regulations.

Disadvantages of biodiesel as an alternative marine fuel:

- Biodiesel's uptake in the maritime transportation sector is limited due to several factors including oxidation stability, controversial food versus fuel issue, high production cost, material compatibility, cold flow properties and lack of marine-grade biodiesel specifications.
- There are concerns about biodiesel's storage conditions, fuel stability, production cost and interaction with various materials in ships.
- Biodiesel consumption can be higher than diesel consumption, resulting in increased fuel consumption of ships and additional land requirements for raw material production.
- The price of iofuels, including biodiesel, is higher than fossil resources, thus it is not economically competitive.
- Bunkering of biodiesel would require the development of proper infrastructure to meet the demand for marine transportation.
- Its uptake in the maritime transportation sector is limited due to various challenges and issues.

See table A for studies that addressed biodiesel.

1.5. Methanol and ethanol

Methanol is considered as an alternative marine fuel for shipping due to its potential environmental benefits and ease of handling (Ampah et al., 2021). It is a liquid fuel at standard temperature and pressure, making it easier to handle compared to other fuels such as liquefied natural gas (LNG). Methanol can be derived from both fossil fuels and biomass. As of 2018, there were already seven methanol-fuelled ships in operation worldwide (Ampah et al., 2021). There are two types of methanol (Ampah et al., 2021):

- Fossil methanol: Methanol produced from fossil sources such as natural gas.
- Renewable methanol: Methanol produced from biomass feedstock. The use of renewable methanol can significantly reduce GHG emissions compared to traditional fuels.

Like other fuels, methanol has advantages and disadvantages which were collected from various studies (i.e. DNV, 2019a, 2019c, 2019b; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Foretich et al., 2021; Maersk Mc-Kinney, 2021; MAN, 2022; WÄRTSILÄ, 2022; Kouzelis et al., 2022; Bilgili, 2023; ClassNK, 2023; Lloyd's Register, 2023b; Raucci et al., 2023).

Advantages of methanol as a marine fuel:

- Easy handling: Methanol is a liquid fuel making it easier to handle compared to LNG.
- Compatibility: Methanol has been used in marine engines and several projects have been conducted to investigate its combustion and viability in the marine fuel market (e.g. METHAPU, SUMMETH, Stena Germainca, Vasa 32, etc.)
- Lower emissions: Methanol-powered vessels have reported lower emissions of SOx, NO_x, PM), and CO_2 compared to traditional fuels like heavy fuel oil (HFO).
- Compliance with regulations: Methanol combustion in marine vessels has shown compliance with Emission Control Areas regulations.
- Lower cost: Methanol investments are relatively lower compared to LNG and it can be cost-competitive with marine gas oil (MGO).

- Methanol has a lower energy density and capital cost and commercial readiness advantage compared to other alternative marine fuels.
- Methanol can be used in marine vessels as a standalone fuel or blended with other fuels like heavy fuel oil or marine gas oil.
- The supply infrastructure for methanol is at a sufficient level and no significant problems are foreseen for bunkering.

Disadvantages of methanol as a marine fuel:

- GHG Emissions: Non-renewable methanol from natural gas can have GHG emissions that are 10% higher than HFO and marine diesel oil (MDO). However, the use of renewable methanol from biomass feedstock can significantly reduce GHG impacts.
- Economic viability: The wide adoption of methanol as a marine fuel depends on its economic viability, carbon credentials being proven and incentivization.
- Fuel cost: Methanol's low calorific value compared to HFO can result in higher fuel costs.

Ethanol is an alcohol-based biofuel produced from biomass sources such as sugarcane, corn or other plant materials. It can be used as a blend with conventional fuels or in dedicated engines (Ampah et al., 2021). The advantages and disadvantage of biofuels (above) are applicable to ethanol. See table A for studies that addressed methanol and ethanol.

1.6. Fully electric batteries

Electricity produced by batteries is considered an alternative marine power source for shipping, particularly for short-range and low-power coastal vessels (Ampah et al., 2021). Battery systems, including different types of batteries (e.g. lithium-ion), provide adaptability to different power demands on ships. Battery-powered solutions are more commonly used in smaller vessels and short-haul shipping at present. Batteries have the advantage of enabling zero-emission operations and offering high efficiency in power generation. However, there are several advantages and disadvantages (limitations) associated with battery usage in shipping which were collected from variety of studies (Balcombe et al., 2019; DNV, 2019a, 2019c, 2019b; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Foretich et al., 2021; Maersk Mc-Kinney, 2021; Kouzelis et al., 2022; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Lloyd's Register, 2023a, 2023b; Raucci et al., 2023).

Advantages:

- Zero emissions: Battery-powered ships produce zero GHG emissions during operation, contributing to overall decarbonization efforts in the maritime sector.
- Energy efficiency: Battery power systems can provide high efficiency, reducing energy losses and improving energy management.
- Noise reduction: Electric propulsion systems utilizing batteries can significantly reduce noise and vibrations compared to traditional engines.
- Smart engines can be connected to the Internet of Things and 5G technologies
- Less maintenance due to fewer rotating parts

Disadvantages:

- High costs: The initial CAPEX for battery systems is generally higher compared to traditional diesel engines, making them less economically attractive for some shipowners, especially for deep-sea (oceangoing) vessels. Some studies revealed that battery costs could exceed the cost of conventional propulsion systems in newbuild vessels.
- Limited range: Battery-powered ships have limited range due to the energy density of batteries. Currently, fully electric propulsion is only feasible for small-sized ships with short sailing distances. The maturity of battery technology for large ocean-going ships is yet to be fully realized as the high costs and limited range makes it less practical for such vessels. However, advancements in battery costs and technology, including decreasing battery prices and improving energy density, are expected to enhance the viability of battery-powered ships over time.
- Charging infrastructure: Availability of shoreside charging infrastructure is limited, requiring investment in onshore facilities for providing electricity to ships.

- Time constraints: The amount of electrical energy transferred from shore to ships depends on factors such as onshore electric grid capabilities and time spent shoreside, which may impose constraints on operations. Thus, adequate charging infrastructure at ports, including onshore electric grid capabilities and battery-charging facilities, is crucial for supporting the widespread adoption of battery-powered vessels.
- Battery lifetime: Batteries need replacement typically every 8-10 years, adding to the operational costs.
- The large size and weight of batteries are also an obstacle to full scale integration.

See table A for studies that addressed batteries.

1.7. Renewable energy capture: Solar

Renewable energy, particularly solar energy, has been considered as an alternative marine power source for shipping. Solar energy can be utilized on ships through various technologies. For example, solar panel systems that use photovoltaic cells to convert sunlight into electricity. Solar panels can be installed on the ship's deck or superstructure to generate power for onboard use. While having the advantage of being widely available, their capacity to meet the power demands of ships is limited. Additionally, solar-assisted propulsion technology is being investigated. It combines solar energy with other propulsion systems to reduce fuel consumption and emissions. It involves integrating solar panels with traditional power systems such as diesel engines or fuel cells to provide supplementary power. Attempts were made to use photovoltaic cells, biofuels or mixtures of petroleum fuels and biofuels and to use electricity batteries charged from the land grid and fuel cells (Dolatabadi et al., 2023; Herdzik, 2023). Solar sails or kites are also used. These devices harness the kinetic energy of sunlight to provide propulsion. Solar sails capture and utilize the pressure exerted by photons emitted by the sun, while solar kites use wind currents at higher altitudes. The first solar system was applied on **Auriga Leader**, a ship of 60,000 gross tonnage which was built by the NYK Line company in 2011, it included about 328 solar panels generating about 10% of the ship's power stationary dock (Nyanya et al., 2021).

There are several advantages and disadvantages of utilizing solar energy in ships which were collected from data from various studies (i.e. DNV, 2019a, 2019c, 2019b; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Maersk Mc-Kinney, 2021; Christodoulou & Cullinane, 2022; Kouzelis et al., 2022; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Dolatabadi et al., 2023; Lloyd's Register, 2023b; Raucci et al., 2023).

Advantages

- Renewable and clean: Solar energy is a sustainable source of power that does not deplete natural resources and does not produce GHG emissions during operation.
- Reduced fuel consumption: Solar power can reduce the reliance on traditional fuel sources, leading to lower fuel consumption and cost savings.
- Independence from external energy supply: Solar energy enables ships to generate their own power, reducing dependence on external energy sources and increasing self-sufficiency.

Disadvantages and challenges

- Limited power generation capacity: Solar panels have limited surface area on board ships, resulting in relatively low power generation compared to the energy demands of ships. On board ships, there is limited space available for installing solar panels, limiting the potential power generation capacity.
- Variability and intermittency: Solar power output fluctuates with weather conditions, such as cloud coverage or the position of the sun, making it less reliable and consistent compared to traditional power sources.
- Cost-effectiveness: The initial installation costs of solar energy systems can be high and the return on investment may take a relatively long time to achieve.
- Infrastructure and maintenance may still be limited in certain areas, hindering the widespread adoption of solar power in shipping.

In terms of characteristics, solar energy is abundant in regions closer to the Equator, as these areas receive higher solar insolation. Thus, solar energy may be more suitable for coastal, island and inland shipping operating within a range of latitude from 30° north to 30° south (Xing et al., 2020). Solar energy in shipping is still considered a developing technology with some studies assessing its feasibility and potential for reducing emissions and fuel consumption. However, these studies highlight the current limitations and challenges, such as cost-effectiveness and limited power density of solar power systems (Dolatabadi et al., 2023; Herdzik, 2023). In summary, solar energy has the potential to contribute to reducing CO_2 emissions and fuel consumption in shipping. However, its limited power generation capacity, variability, cost-effectiveness and infrastructure challenges need to be considered when evaluating its application in maritime operations.

See table A for studies that addressed solar energy.

1.8. Renewable energy capture: Wind energy

Wind energy has long been recognized as a viable and abundant renewable energy source for ships. It can be utilized as an alternative marine power for shipping, reducing the reliance on fossil fuel-based propulsion systems. The following are two types of wind capture on board ships and their advantages and disadvantages which were collected from various studies (Balcombe et al., 2019; DNV, 2019b, 2019c, 2019a, 2023; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Maersk Mc-Kinney, 2021; Kouzelis et al., 2022; MAN, 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Dolatabadi et al., 2023; Herdzik, 2023; Lloyd's Register, 2023b; Raucci et al., 2023).

1.8.1. Sail-based wind energy systems

One of the most traditional and well-known forms of wind energy utilization in ships is sail-based systems. Sails capture the wind's kinetic energy and convert it into a propulsive force for the vessel. This approach has been used for centuries in maritime transportation.

The sail-based wind energy offers the following advantages:

- Abundance of wind energy: Wind is a renewable resource available in most parts of the world, providing unlimited potential for energy generation. It is considered more suitable for maritime transportation than on-land utilization due to lower frictional reduction in velocity.

- Carbon-neutral operation: Sail-based systems do not produce direct CO_2 emissions, contributing to a greener and more sustainable shipping industry. Utilizing wind energy for maritime transportation can lead to significant fuel and emissions reductions compared to conventional ship fuelling options.
- Reduced fuel consumption: By harnessing the power of wind, ships can reduce their reliance on conventional propulsion methods, leading to reduced fuel consumption and lower operational costs.
- Cost reduction: Wind energy can be used as an additional source of power to support conventional ship propulsion systems, leading to desired cost reductions.
- Increased thrust: Wind sails can reduce propeller thrust by approximately 10% when the ship sails at 10 knots in 13 knots of wind. Decreasing the ship's speed can further increase the contribution of wind sails to the thrust.

However, sail-based wind energy systems also have some limitations:

- Dependence on wind conditions: The effectiveness of sail-based systems relies heavily on wind speed, direction and consistency. Ships may experience difficulties maintaining their intended course when faced with unfavourable wind patterns.
- Restricted manoeuvrability: Sail-based systems may limit a ship's manoeuvrability, potentially impacting its ability to navigate efficiently in congested or constrained waters.
- Space requirement: Effective utilization of sail-based systems requires ample deck space for the installation and deployment of sails which may be challenging for certain ship types, such as container ships or cruise ships.

1.8.2. Wind-assisted propulsion systems

In addition to traditional sails, modern wind-assisted propulsion systems have emerged as a promising technology for utilizing wind energy in ships. These systems incorporate advanced mechanisms, such as wingsails, Flettner rotors or kites, to capture wind energy and provide supplemental propulsive force.

The advantages of wind-assisted propulsion systems include:

- Enhanced efficiency: Wind-assisted systems can augment or optimize a ship's conventional propulsion system, leading to improved fuel efficiency and reduced carbon emissions.
- Adaptability to ship routes: Wind-assisted systems can be modified or adjusted based on specific ship routes and wind conditions, allowing for maximized energy generation.
- Compatibility with existing infrastructure: Wind-assisted systems can be integrated into existing ships without extensive modifications, making it a practical option for retrofitting vessels.
- Combined power systems: The development of a combined thermal-wind-photovoltaic power system with an optimal generation plan can also lead to desired cost reductions.
- Mature terodynamics Theory: The aerodynamics theory for wind-assistance systems is mature and there is ongoing research and practice on the application of wind-assistance systems on ships (see table A)
- Wind-assisted systems have fuel savings: Wind-assisted propulsion has already delivered yearly fuel savings of between 5% and 9% for certain ships and has the potential to reach 25% fuel savings. The gains can be higher if newbuilds are specifically designed to carry sail systems (DNV, 2023).
- Unlimited power source: The availability of wind as a power source is unlimited. However, the quantity and quality of wind energy may vary due to meteorological changes.

However, wind-assisted propulsion systems also have their limitations (disadvantages):

- Variable power generation: The output of wind-assisted systems relies on fluctuating wind conditions, resulting in variable power generation. This inconsistency may require supplementary power sources to ensure continuous operation.

- Initial investment and maintenance costs: Implementing wind-assisted propulsion systems may involve significant upfront costs, including the installation and maintenance of complex equipment. However, potential fuel savings over the operational lifespan of the system can offset these costs.
- Limited effectiveness in certain conditions: Wind-assisted systems may experience reduced effectiveness during certain weather conditions, such as low wind speeds or adverse wind directions.

It is worth noting that the adoption of wind energy in ships is influenced by several factors, including:

- Ship type and size: Some ship types, such as bulk carriers or oil tankers, may have more space and stability to accommodate wind energy systems compared to smaller vessels or those with specific design requirements.
- Regulatory environment: Regulatory frameworks and international standards play a crucial role in incentivizing or mandating the adoption of wind energy technologies in ships.
- Cost-effectiveness: The financial viability of wind energy systems is a key consideration for shipowners and operators. The overall cost-benefit analysis, including fuel savings, operational efficiency, and environmental impact, determines the economic advantages and disadvantages.

The maturity and usage of wind energy in ships can vary depending on the specific type of wind energy application. Sail-based systems, with their long history, have reached a relatively high level of maturity and can be found in niche markets, such as eco-tourism or historical replica vessels. On the other hand, wind-assisted propulsion systems are considered more innovative and are gaining traction in the maritime industry. Several pilot projects and research studies have been conducted to assess their feasibility and potential benefits (e.g. Viola et al., 2015; Rehmatulla et al., 2017; Lu & Ringsberg, 2019; Nyanya et al., 2021; Lindstad et al., 2022; Dolatabadi et al., 2023; Formosa et al., 2023; Thies & Ringsberg, 2023; Vigna & Figari, 2023). See table A for studies that addressed wind energy.

1.9. Carbon capture and storage

Carbon capture in shipping refers to the process of capturing and storing carbon dioxide (CO_2) emissions produced by ships. It is a technology that aims to reduce the GHG emissions from the shipping industry and contribute to the goal of achieving net-zero shipping. Onboard carbon capture in shipping involves capturing CO_2 from the exhaust after the fuel has been burned. This can be done through various methods such as chemical absorption (utilises a chemical solvent to absorb the CO_2 from the exhaust gas.), membrane separation (requires passing the exhaust gas stream through a set of membranes that separate several components in the gas from each other), pressure swing absorption (exploits the tendency of gases to be attracted to solid surfaces under high pressure, thereby allowing the separation of CO_2 from exhaust gas), or cryogenic capture technologies. Currently, the most popular method for onboard carbon capture is chemical absorption using amine solvents, which is considered mature for shore-based applications (DNV, 2023).

The use of onboard carbon capture in shipping is not yet widely implemented, but there are ongoing efforts to prove its usability for ships. Hence, CCS technologies in maritime applications are still at an early stage and future prospects depend on technological innovation and policy support. Several companies are working on developing and testing carbon capture systems for onboard use (DNV, 2023). Under development CCS for ships is the Calix RECAST design for scrubbing exhaust gas, which can capture up to 85–90% of the CO_2, while the heat generated in the exothermic reaction can be reclaimed as power (or integrated within an existing WHR system) thereby reducing the fuel consumption (Balcombe et al., 2019). While the cost of the CCS technology is high, the feasibility and economic viability depend on factors such as the fuel penalty (extra energy used for operating the capture unit) and the CO_2 deposit cost (sum of CO_2 transport and storage costs).

There are several advantages and disadvantages for CCS, based on studies that presented CCS (Cuéllar-Franca and Azapagic, 2015; DNV, 2019a, 2019b, 2023; Al-Enazi et al., 2021; Ampah et al., 2021; Dos Santos et al., 2022; Bilgili, 2023).

Advantages:

- Significant reduction in CO_2 emissions.

- It is considered a potential decarbonization strategy for meeting future GHG regulations.
- Can be combined with other technologies for enhanced performance.

Disadvantages:

- Expensive initial investment cost.
- Availability of infrastructure is an issue as CCS technology requires the availability of carbon offloading infrastructure, CO_2 transportation and permanent storage facilities for its implementation.
- The costs of onboard CCS in shipping isare high and depend on factors such as the installation cost of the capture and storage facilities, additional operating costs and fuel consumption, and the cost of delivering captured CO_2 to reception facilities.
- CCS is faced with several technical challenges regarding system integration and optimization. For retrofitting on existing ships, it is worth noting that both the carbon capture technology and storage facilities for CO_2 need space and will add considerable weigh to ships.
- Reasonable technological development required for future prospects including CO_2 market.

There are other ways for the treatment of the exhaust gas, i.e. options to decarbonize ships once residual fuels are used. These include the Selective Catalytic Reduction (SCR), ammonia slip catalysts and exhaust gas recirculation (EGR), though the technology it is still under development. The development of methane oxidation catalysts would also improve the potential of such technologies (Balcombe et al., 2019). Overall, while onboard carbon capture technology is being explored and researched for use in the shipping industry, it is not yet widely used, and further advancements and cost optimizations are needed for its widespread adoption. See table A in the Appendix for studies that addressed CCS.

1.10. Nuclear energy

Nuclear energy technology has been considered as an alternative marine power source for ships although its widespread use in the near future may be unlikely. On board ships, nuclear power (propulsion) can be produced via a small nuclear plant that heats water to build steam for driving steam turbines and turbo generators. Nuclear-powered marine propulsion has mainly been used in military vessels and icebreakers. Only four nuclear-powered merchant ships have been built, but none have proved profitable. While it remains an early-stage concept, the uptake in the commercial sector may make use of small modular reactor (SMR) technology, sized at a few hundred MW, for instance, the 'RITM-200' reactor for icebreakers such as the **NS Arktika**, with a seven-year refuelling cycle. The cost of two 175MW steam generators is approximately $1.9 billion per vessel (Balcombe et al., 2019). The operation of nuclear-powered vessels would require marine engineers who are qualified in nuclear reactor operation. The Maritime Forecast to 2050 report by DNV analysed the outlook for ship technologies and fuels, including nuclear propulsion as a zero-emission and carbon-neutral alternative (DNV, 2023). Following are several advantages and disadvantages of nuclear energy (Balcombe et al., 2019; DNV, 2019b, 2023; Xing et al., 2020; Al-Enazi et al., 2021; Dos Santos et al., 2022; Lloyd's Register, 2023b).

Advantages of nuclear energy for ships:

- No need for frequent refuelling.
- More cargo space.
- Higher power and speed.
- No air pollutants and GHG emissions.

Disadvantages of nuclear energy for ships:

- Expensive initial investment and operational costs.
- Limited research and development in future nuclear applications.
- The control of nuclear material is a substantial security and geopolitical concern, thus development of commercial (civilian) nuclear ships faces public, political and legislation issues. Indeed, non-proliferation issues, international regulatory development and public perception are barriers to widespread use.

- Safety is another issue, particularly against catastrophic accidents (liability issues), radioactive pollution to air and water from fires or sinking of nuclear-powered vessels, terrorism.
- The availability of bunkering infrastructure for nuclear-powered ships is limited.

See table A for studies that addressed nuclear energy.

1.11. Hybrid power systems

Hybrid power systems are considered alternative marine power for ships. These systems combine multiple power sources, typically including fuel cells, wind power and solar energy, and batteries to provide propulsion and reduce CO_2 emissions in ships. The wind-assisted propulsion utilizes wind energy through wind turbines, Flettner rotors, Skysail and sails to supplement or replace traditional power sources, solar energy can be used as an auxiliary power source in certain ship types, while fuel cells utilise zero or near-zero GHG emission fuels like hydrogen and ammonia. Based on variety of studies (i.e. Balcombe et al., 2019; DNV, 2019a, 2019c, 2019b, 2023; Kim et al., 2020; Xing et al., 2020; Ampah et al., 2021; Foretich et al., 2021; Maersk Mc-Kinney, 2021; Kouzelis et al., 2022; WÄRTSILÄ, 2022; Bilgili, 2023; ClassNK, 2023; Dolatabadi et al., 2023; Herdzik, 2023; Lloyd's Register, 2023b; MAN, 2022; Raucci et al., 2023), below are advantages and disadvantages of hybrid power systems bearing in mind that the advantages and disadvantages of technologies presented above are applicable here as these technologies form part of the hybrid systems.

Advantages of hybrid power systems

- Hybrid power systems have the potential for reducing CO_2 emissions, utilizing renewable energy sources and diversifying the power sources for increased energy efficiency.
- Hybrid power systems and systems optimized for specific ship types and routes are believed to have the best prospects for reducing CO_2 emissions at this stage.

Disadvantages

- Characteristics, maturity, and usage of hybrid power systems in maritime applications vary.
- Regarding bunkering and infrastructure, fuels that supply hybrid power systems are not available on a large scale, specifically hydrogen and ammonia as fuel cells.

Studies have been conducted to evaluate the feasibility and potential of hybrid power systems for maritime applications. For example, studies by DNV evaluated the potential and constraints of fuel cells including renewable energy for shipping, as part of hybrid systems, providing a guide for technical feasibility and risk-based analysis (DNV, 2019c, 2019b, 2019a, 2023). Another study assessed the technical feasibility of a hybrid propulsion system for bulk carriers, combining hydrogen fuel cells with wind and solar energy, aiming for zero-emissions shipping (Dolatabadi et al., 2023). Other studies also considered and evaluated the potential of different hybrid systems onboard ships, e.g. wind sail and solar power (Nyanya et al., 2021), hybrid PVs, battery and diesel engine (Lan et al., 2015), battery/hybrid propulsion vessel (Kolodziejski & Michalska-Pozoga, 2023), hybrid propulsion systems (HPSs) of hydrogen and batteries for electricity (Fan et al., 2022). See the rest of the studies in table A

2. Life Cycle Analysis (LCA) studies

This section presents the review on the LCA studies based on the search results. There are around thirty studies that contains LCA literature review. Therefore, this section provides a comprehensive overview of the LCA application in the maritime industry in general, and specific studies are presented in table B based on the criteria for data extraction.

The LCA method is a tool that can provide a holistic view of a product's life cycle. The LCA work contains four main phases, namely (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation. For more information about the basic knowledge of LCA, please refer to ISO 14040. It is worth noting that the International Council on Clean Transportation report (Key issues in LCA methodology) highlighted that those fuels should be sustainability-certified to have less LCA emissions (Carvalho et al., 2023). This includes "(1) renewable electricity is used for e-fuels and it is additional; (2) biofuels are not grown on high-carbon-stock land; and (3) fuels made from captured carbon are not double-claiming emissions reductions for carbon capture."

2.1. Ammonia, hydrogen, biofuels

The LCA of hydrogen in the maritime industry was conducted in Bicer and Dincer (2018), Lee, Jung et al.(2020), Alkhaledi, Sampath et al.(2022), Sullivan (2022_), Evers, Kirkels et al. (2023), Sánchez, Martín Rengel et al. (2023), Wang, Aung et al.(2023) and Wang, Zhao et al.(2023). In general, the results in most studies show the GHG reduction by using hydrogen in maritime industry. For example, Bicer and Dincer (2018) indicated that hydrogen powered vessels can reduce up to 33.5% of GHG emissions, compared to heavy fuel oils. However, it is necessary to be careful to consider the production pathway of hydrogen (Lee, Kim et al., 2022). The advantage of using hydrogen is that, in the tank-to-wake phase, there are no carbon emissions (except for the use of pilot fuel); while the hydrogen storage requires a very low temperature and a considerable amount of energy is required for this process. Using hydrogen also brings the economic benefit as indicated by (Alkhaledi, Sampath et al., 2022, Wang, Aung et al., 2023).

The environmental performance depends on the type of ammonia used. For example, brown/grey ammonia can bring worse CO_2 emissions than fossil fuels (Zincir, 2022). It is indicated in Galucci (2021) that, using ammonia/ammonia fuel cells can help the shipping industry reduce up to 50% of GHG emission. The difference from the above studies shows that to gain the environmental benefits from ammonia in shipping industry, the upstream process (ammonia production) plays an important role. In terms of cost, green ammonia is not competitive nowadays without any actions on carbon tax. For more information about the application of ammonia and hydrogen in the maritime industry, please refer to the literature review work that has been done before (Evers, Kirkels et al., 2023).

From the search results, there are another three alternative fuels-related articles (Hua, Wu et al., 2017) (Xinping, 2022) (Bengtsson, Fridell et al., 2012) (Stathatou, Bergeron et al., 2022). The findings show that biofuels can have positive impacts on the maritime industry, with about 50% GHG reduction, compared to fossil fuels (Bengtsson, Fridell et al., 2012). However, it could increase the other environmental categories such as eutrophication and primary energy use. LNG is also a potential candidate for maritime decarbonization, but the methane slip can be controlled (Hua, Wu et al., 2017).

It is worth noting that a report entitled "Additionality of renewable electricity for green hydrogen production in the EU" addressed the hydrogen production from renewable electricity (CE Delft, 2022). "The concept of additionality refers to the requirement that new electrolysers producing renewable hydrogen must be supplied by electricity from new, dedicated renewable sources". The report highlighted that, in order to minimise CO_2 emissions during the energy transition, strict adherence to the additionality requirement is necessary.

2.2. Batteries, electrification

Using batteries could reduce the environmental impacts, around 9% of GHG reduction (Peralta P, Vieira et al., 2019) and up to 35.7%, compared to diesel powered vessels (Jeong, Jeon et al., 2020). However, it is again emphasized that the environmental performance of battery technology depends on the source of electricity generation (Jeong, Jeon et al., 2020). Furthermore, GHG reduction could be achieved by optimizing the energy system (Peralta P, Vieira et al., 2019). The end-of-life of batteries and the material resources (for producing batteries) could be carefully considered.

2.3. Solar energy

The benefit of using solar energy in the shipping industry depends on the upstream/power production phases. For example, a PV-equipped ship reduced 40,812 kg CO_2eq. per year in Brazil while achieving greater reductions in India and Australia due to coal-based power production (Park, Jeong et al., 2022). The advantage of using PV systems is that they require lower maintenance costs, compared to a conventional propulsion system (Abdullah-Al-Mahbub, Towfiqul Islam et al., 2023).

2.4. New LCA method for maritime industry

A new LCA method for the shipping industry (Live-LCA) was presented in (Park, Jeong et al., 2022). This new method can overcome any limitation in conventional LCA and can support to evaluate the environmental performance of vessel fleet. For more information, please refer to table B.

2.5. Remarks about the studies

From the description of the article, some suggestions have been made as follows.

- First, the selected paper did not use any specific guidelines for the maritime industry (only the ISO 14040 that is quite broad). Therefore, it is necessary to have a concrete guideline/standard for LCA practitioners to apply this method for the maritime industry. The standard/guideline can contain not only the instruction for LCA of marine fuels, but also contain the topics of LCA for vessels, marine engines, etc. Furthermore, the guidelines for the LCA report in the maritime industry can also be prepared. The results and conclusion from these papers are for reference only.
- Second, there is still a lack of a standardized method in the scientific literature for assessing the environmental impact of the maritime industry. There is limited knowledge about vessel disposal processes within the maritime sector. The life cycle assessments that consider the entire lifespan of vessels lack consistency in allocation models.
- For the use of optional stages in the LCA, i.e. normalisation, weighting method, there are no studies mentioned in this regard. There is a need for a guideline specific to maritime on how to use the data for conducting the LCA. The data can be adequate and up to date.
- Finally, a new LCA method (Park, Jeong et al., 2022) can also be considered and investigated to exploit the advantages of LCA.

In conclusion, the application of LCA in the maritime industry is driving significant positive changes. It facilitates reductions in the industry's environmental footprint, ensures compliance with regulations, promotes sustainable ship design, improves fuel efficiency, fosters transparency and encourages a commitment to continuous improvement. This approach not only benefits the environment but also aligns with the industry's long-term economic and social responsibility goals.

Table A. Studies that address the decarbonization technologies

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Technical: quantifies the fuel consumption of a combined propulsion system consisting of a diesel engine and a controllable pitch propeller (CPP) assisted with one or more wind Flettner rotors	Wind (Flettner rotors)	A 3,000-ton Ro-Ro/Pax ferry	5% to 10% for the power savings	4% to 6% for fuel consumption savings	NA	Mediterranean Sea	Combination of rotors and CPP could reduce fuel consumption up to 15%	(Vigna & Figari, 2023)
Technical: investigation of wind-assisted ship propulsion of a series 60 ship using a static kite sail	Static kite sail	75 m long ship having a Series 60 hull	Potential	NA	NA	Modelling (simulation)	The static 320 m^2 kite sail at a height of 90 is sufficient to meet the entire propulsion requirements under appropriate wind conditions (when the wind speed is 20 m/s and vessel speed is 5.3 m/s)	(Formosa et al., 2023)
Technical: analyses the engineering considerations of the storage of alternative fuels on board large scale international vessels	Ammonia, hydrogen, methanol	Large LNG tanker	Zero carbon by mixture of technologies (or green hydrogen and fuel cells)	NA	NA	Modelling (simulation)	Methanol required less mass and volume than ammonia, and less volume and is easier to store than hydrogen. Hydrogen has a perceived low volumetric energy density, and volume required is 6,500 m3 for liquid storage (85 containers), which is not very high to be considered inviable	(McKinlay et al., 2021)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Technical: applying ennobled solid biomass via mechanical compaction or torrefaction as fuel for ships	Solid biofuels	Ro-Pax ferry type,	Potential	NA	Available	Baltic Sea	The technology is potential but there are potential fire hazards on the ship resulting from the storage and transport of pellets, and from pellets after torrefaction	(Zeńczak & Gromadzińska, 2020)
Technical: proposes a method for determining the optimal size of the photovoltaic (PV) generation system, the diesel generator and the energy storage system in a stand-alone ship power system that minimizes the investment cost, fuel cost and the CO_2 emissions	PV/ESS	Bulk ship	Potential	NA	Yes (through Multi-Objective Particle Swarm Optimiza-tion (MOPSO))	Route from Dalian in China to Aden in Yemen	The acquired net present cost of hybrid PV/diesel/ESS power generation is less than that of PV/diesel power generation	(Lan et al., 2015)
Management: the role of politics in accelerating energy transitions within the maritime sector	Electrification	Ferries	Potential	NA	NA	Norwegian ferry sector	Suggested a set of success criteria for accelerating energy transition	(Sæther & Moe, 2021)
Technical: presenting numerical investigation on the potential of	Wingsails	KVLCC2M hull	Potential with several tall wingsails	NA	NA	Simulation	The wingsails allow a maximum propeller thrust reduction of about 10% when the ship	(Viola et al., 2015)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
wind-assisted propulsion for merchant ships							sails at 10 knots in 13 knots of wind, or if she sails at 8 knots in 10 knots of wind	
Technical: the suppression of hydrogen jet fires on hydrogen fuel cell ships using a fine water mist	Hydrogen	NA	NA	NA	NA	Simulation	Mist is not effective in extinguishing hydrogen jet fires, but stronger droplets can reduce their development	(Yuan et al., 2021)
Technical: Review of Power Converters for Ships Electrification	Electrification	Different ships	NA	NA	Yes	Review	Presents a comprehensive topological review of currently-available shore-to-ship and shipboard power converters in the literature and on the market	(Mahdi et al., 2022)
Technical: presents types of energy storage and battery management systems used for ships' hybrid/electric propulsion	Electrification and hybridisation	Different ships (ferries)	Yes (different projects results)	Yes (different projects results)	Yes (different projects results)	Yes (different projects results)	Presented various electrification and hybridisation projects	(Kolodziejski & Michalska-Pozoga, 2023)
Policy: present technological innovation system (TIS) framework to the field of maritime transportation	Battery-electric and hydrogen energy solutions	Coastal ships	NA	NA	NA	Norway	There is a need for public procurement and policy instruments to enable technologies integration and developments	(Bach et al., 2020)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Technical: Investigating energy storage, diesel generators and PV panels onboard	energy storage system (ESS)	Ferry ship	Potential	ESS reduces 5.52% of CO_2 emission	Yes	NA	The proposed a flexible and effective integrated Power System (IPS)	(Bao et al., 2021)
Technical: investigates incorporating renewable feedstocks and energy in the production of green ammonia and evaluates the techno-economic and environmental impacts	Green ammonia	NA	Potential	NA	Yes	NA	Geen ammonia is a good option for shipping decarbonization, but higher production based on renewable energy is required	(Al-aboosi et al., 2021)
Review: synthesise the literature to provide an overview of main challenges and opportunities along potential supply chains of renewable methanol for maritime shipping	Bio-methanol	NA	Potential	NA	NA	Yes (discussion of all economic aspects)	The feedstock and supply, production and economics were presented	(Svanberg et al., 2018)
Technical: discuss safety considerations of hydrogen application in shipping	Hydrogen	NA	Potential	NA	NA	NA	Proposed a method that can help to enable a wider, but still safe, use of hydrogen in shipping	(Depken et al., 2022)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Technical: discuss safety issues for ammonia use onboard	Ammonia	114,000 GWT LNG tanker	Potential	NA	NA	Simulation	Ammonia does have a high risk due to its toxicity but a low risk in terms of flammability. Research findings also demonstrate that the gas dispersion depends on numerous factors	(Yadav & Jeong, 2022)
Technical: investigates using blue/green ammonia as a marine alternative fuel from environmental and economic points of view	Blue/green ammonia	Ro-Ro ship	Potential	92% reduction of GHG compared with the traditional propulsion system	Total ship saving cost of 5.71% and annual levelized cost of energy 0.19 $/kWh	Mediterra-nean Sea	Solid oxide fuel cell (SOFC) green ammonia-fuelled ship proposes to be eco-friendly with cost effectiveness of 172.92 $/ton- emissions	(Seddiek & Ammar, 2023)
Technical: proposed the integrated design of an NH3 fuel supply system and a re-liquefaction system for an ocean-going NH3-fuelled ship	Ammonia	14,000 TEU large container ship	Potential	NA	Yes	Traveling between Asia and Europe	According to LCC, NH3 fuel is economically feasible if the carbon tax is more than $ 80/ton and the NH3 price is around $ 250/ton	(J. Lee et al., 2022)
Technical: assesses the technical feasibility of a hybrid propulsion system for bulk carriers, combining	Hydrogen and wind and solar energy	Bulk carriers	Potential	NA	Yes	Be applied to specific routes, under	Wind power, solar power, and hydrogen fuel cells can cover 8 to 27%, less than 1%, and 50 to 100% of the total required power for	(Dolatabadi et al., 2023)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
green hydrogen with wind and solar energy						specific conditions	propulsion correspondingly depending on (distance, speed and ship size)	
Technical: Electrification of ships using the northern sea route	Batteries and renewable energy	180,000-tons bulk carrier	Potential	NA	NA	Northern sea route	Under current economic conditions, the solution would not be profitable as it stands, but can become so at a later stage	(Savard et al., 2020)
Technical: optimisation of rigid windsail angle under varying wind conditions, and optimisation of available deck area to maximise wind and solar total power production	Wind and solar	Bulk carrier	Potential	36% reduction of CO_2, and 100% reduction if ship speed was reduced to 56% of its original speed	NA	Global trade routes	Sailing at optimal sail angle and optimising the available deck area with combined installation of solar and wind system allowed maximising the renewable power production	(Nyanya et al., 2021)
Policy and technical: provides a systematic analysis of the viability of wind technology on ships and the barriers to their implementation, both from the perspective of the technology providers and	Wind	Oil tanker	Potential	NA	NA	Simulation	Third party capital is a plausible solution to overcoming the cost of capital, split incentives and information barriers	(Rehmatulla et al., 2017)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
technology users (shipowner–operators)								
Technical: compares wind propulsion solutions and battery storage possibilities	Wind & ESS	Ro-Ro ship	Potential	100% emission reduction in using hybrid tech	NA	Baltic Sea	Presented the suitable wind technology and how battery packs reach zero-emission operation	(Thies & Ringsberg, 2023)
Technical: investigate a technology that exploits cold exergy from liquid hydrogen and low temperature waste heat from fuel cell	Hydrogen & fuel cells	NA	Potential	40.45% energy efficiency	11.2 years payback and the NPV was $295,268	NA	Presented the potential viability of the system (Rankine cycle-direct expansion cycle (ORC-DEC))	(H. Lee et al., 2023)
Technical: thermodynamic analysis of integrated ammonia fuel cells system to exploit waste heat	Ammonia & fuel cells	General cargo (electric propulsion)	Potential	Energy and exergy efficiency of 60.69% & 57.50%	NA	NA	The integrated system achieved a power output of1634.46 kW from the waste heat recovery subsystems, accounting for 30.08% of the total power supply	(Duong et al., 2023)
Technical: analysis of the physical and chemical properties of various pure vegetable oils as an alternative	Pure vegetable oils	All ships	Potential	Neutral CO_2 saving	NA	NA	Pure vegetable oils have potential as alternative fuels to HFO used in the low-speed diesel engines of large ships	(Jiménez Espadafor et al., 2009)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
to heavy fuel oil for large ship propulsion								
Technical: analysis of hydrogen leakage and explosion behaviours in various compartments on a hydrogen fuel cell ship	Hydrogen	Passenger ship	Potential	NA	NA	Simulation	Proposed the appropriate design scheme, management method and escape measures to reduce the risk of leakage accidents on the ship and enhance the safety of HFCS	(Mao et al., 2021)
Technical: compare wind-assisted ship propulsion technologies	Flettner rotor, wingsail and DynaRig	Aframax oil tanker	Potential	5.6% to 8.9% fuel saving	NA	Route between Gabon and Canada (simulation)	Flettner rotor can be compatible with ship type, speed, voyage routes and corresponding weather conditions to achieve as large fuel savings	(Lu & Ringsberg, 2019)
Technical: potential energy reductions through building more slender bulk vessels in combination with wind assisted propulsion (WASP)	Wind assisted propulsion	Slender bulk vessels	Potential	30%-40% GHG emission reduction	NA	NA	Fuel consumption and hence GHG emissions can be reduced by up to 40% on an operational basis (EEOI) and 30% when shipbuilding is included (LCA)	(Lindstad et al., 2022)
Technical: propose semi-online parameter identification	Lithium battery (P-LiB)	All-electric ship	Potential	NA	NA	Simulation	The semi-online identification method obtained promising performance (accuracy, timeliness and optimal length)	(Tang et al., 2023)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
methodology for maritime power lithium batteries								
Technical: proposes a coordinated operation strategy for a ship micorgird with hybrid propulsion systems	Hydrogen fuel cells and batteries	Any ship	Potential	NA	NA	Simulation	Proposed a strategy that can guarantee the feasibility of the operation scheme for the whole voyage.	(Fan et al., 2022)
Policy: presents an analysis of the drivers for and barriers to increased biogas usage in three sectors	Biogas	NA	NA	NA	NA	Sweden	Reiterated the significant influence of policy in the form of subsidies, tax exemptions and regulations on the adoption and use of biogas	(Dahlgren et al., 2022)
Review: reviewed the pertinent knowledge in the field, associated with the production, storage, and energy-derivation of hydrogen on ships and aims to identify the potential issues and provide possible solutions for fueling the shipping industry with hydrogen energy	Hydrogen	Different ships	Potential	NA	Available	NA	Considering different disadvantages (space, costs, retrofitting etc.), cheaper conventional fuels leading to the reluctancy of industry players to become involved in such a green transition	(Tuan et al., 2023)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Environmental/Cost	HFO/LNG/hydrogen/ammonia/methanol/biodiesel/electricity	-	Comparison of different fuel production pathways	100% reduction for solar based hydrogen	The cost increases approxima-tely five times comparing HFO scenario	NA	Renewable electricity with battery provides the best solution. The second-best solution is fossil fuels with CCS.	(Law et al., 2021)
Environmental/Cost	HFO/ammonia	Container	Comparison of HFO and ammonia with different pathways	83.7-92.1% of GHG reduction in case of ammonia usage	The cost increases at least 2.3 times in case of ammonia usage.	NA	The study concluded that an ammonia-based electric propulsion system powered by SFOC is the most environmentally-friendly method. In this method, the total GHG emissions decrease up to 3.8 t of CO_2eq compared to 48.4 t of CO_2eq emitted in case of using HFO.	(Kim et al., 2020)
Environmental/Technical	Hydrogen/ammonia/methanol	NA	Comparison of the green fuels	NA	NA	NA	Advantages and disadvantages of the fuels are explained in detail.	(Shi et al., 2023)
Environmental/Technical/Cost	LNG/hydrogen/ammonia	NA	Review on the fuels	NA	NA	NA	Hydrogen is a favourable option but the cost of storage, handling and transportation may	(Al-Enazi et al., 2021)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
							cause serious concerns. Ammonia can be easily used in the engines and turbines but has a disadvantage for toxicity. LNG is a very promising transition fuel and the infrastructure for LNG is at an adequate level.	
Environmental/Technical/Cost	Ammonia	NA	Review on ammonia	NA	NA	NA	Although ammonia is a promising zero carbon fuel for the future, it has some disadvantages such as high production costs, availability, competition with the fertiliser industry and lack of regulations on toxicity, safety and storage.	(Mallouppas et al., 2022)
Environmental	PV-based electricity	Cruise ship	Electricity application	7.9% reduction in pollutants	186-188 million INR for the initial cost, 25 million per year INR for the operating cost	Implementa-tion on a cruise ship	Solar-based electricity system instalment on a cruise ship can cause 9.2% reduction in fossil fuel consumption and 7.9% reduction in pollutants	(Krishnamoorthy et al., 2021)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
In all aspects	Hydrogen/ammonia/NG/methanol/ethanol/DME/bio-diesel/	NA	NA	NA	NA	NA	Although hydrogen and ammonia seem to be one of the most promising ways due to their zero-carbon content, the costs are quite high and, thus, they are far from being applicable on a worldwide scale. Therefore, CCS is recommended to be used in parallel with the other fuels.	(Xing et al., 2021)
Cost	Ammonia	Container ship	NA	NA	NA	NA	Although the great benefits for the environment due to its carbon-free content, the cost highly depends on the fuel price, which is quite high now and unpredictable for the future.	(Gerlitz et al., 2022)
Environmental/Cost	Methanol	Container ship	-	18.3% reduction in CO_2	-	A cellular container ship	Using methanol (89%) and diesel (11%) in a dual-fuel engine results in a significant decrease in the total amount of diesel which leads to a reduction of various emissions. Total CO_2 emissions decrease by 29.320 t per year.	(Ammar, 2019)
Environmental/Cost	Hydrogen/Ammonia/Metha	Cruise ship	NA	NA	NA	A cruise ship operating in the Caribbean	SOFC, PEMFC, D-ICE, and S-ICE were applied in 10 scenarios. According to the results, hydrogen SOFC system presents the highest	(Zhang et al., 2023)

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	nol/Natural Gas						energy efficiency, while all alternative fuels with ICE present the lowest values.	
Environmental/Infrastructural/Cost /Technical	Fossil fuels/LPG/LNG/methanol/SVO/HVO/biodiesel/biocrude /bio-oils/ammonia /hydrogen	NA	NA	NA	NA	NA	The results of the study show that HTL-biocrude may show the best environmental performance in terms of life cycle GHG emissions.	(Foretich et al., 2021)
Environmental/Cost	Biofuels/LNG/ nuclear	-	Innovative ideas on emission reduction	NA	NA	NA	In this early study, 2050 pathways were investigated. In case of using biofuels, LNG, and nuclear energy altogether, the emissions are estimated to be decreased by up to 90%.	(Eide et al., 2014)
Energy/Environmental/Economic	Hydrogen/Methanol/Ammonia/LNG	Cruise ship	NA	NA	NA	A large-size cruise ship with 3,700 passenger capacity operating in the	In all scenarios for different geographic locations, ammonia usage results with the greatest GHG reduction, as expected.	(Dotto & Campora, 2023)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
						Mediterra-nean, North Sea, Caribbean Sea, Red Sea		
Environmental	Ammonia	NA	NA	22% reduction in GHG emissions	NA	Modular Ship Emission Modeling System (MoSES)	The study mainly focused on the results of ammonia usage as a primary energy source for a long-term (2050) target. While using ammonia with a pilot fuel (MGO) decreases CO_2 emissions by up to 40% by 2050, only 22% reduction can be occurred in GHG emissions due to the nitrogen content of ammonia.	(Schwarzkopf et al., 2023)
Environmental/Technical	Hydrogen/ Wind	Tanker	Flettner rotors and hydrogen	3.5% reduction in NO_x emissions	NA	Tanker operating between Marseille-Algeria and Tangier-Southamp-ton	While hydrogen is used as the primary energy source, Flettner rotors provide supporting acceleration which results in 3.5% reduction in NO_x emissions.	(Alkhaledi et al., 2023)

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Environmental/Technical/Cost	Methanol	Passenger ship	Dual-fuel engine with methanol and MDO	28-30% reduction in CO_2	NA	Two passenger ships operating in Indonesia	Two passenger ships operating in Indonesian waters are investigated and a dual-fuel engine using methanol and MDO is implemented. 28-30% reduction is expected in CO_2 emissions.	(Priyanto et al., 2021)

Table B: Life Cycle Assessment (LCA) studies

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Technical, LCA of H2 vessels, literature review	H2 propulsion system and vessels	N/A	Use of H2 onboard vessels	N/A	N/A	N/A	Focusing on developing requirements for sustainable maritime vessels. It highlights the significance of the Maintenance, Operation, and Lifecycle (MOL) phase and discusses challenges and opportunities related to shifting towards hydrogen and renewable fuels.	(Sullivan, 2022)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Hydrogen + ammonia blend	N/A	Large ferry	N/A	N/A	N/A	H2MetAmo project	Using ammonia-hydrogen blend for an internal combustion engine, onboard hydrogen production and emissions control measures. The total capital cost is 8.66 M€ (784 €/kW), with potential cost reductions due to decreasing green ammonia prices, making ammonia-based ships a competitive option for decarbonizing maritime transportation.	(Sánchez et al., 2023)
Literature review about LCA of H2 and NH3, applied for vessels	H2 and NH3, fuel cell	All	Alternative fuel	N/A	N/A	N/A	Literature review was conducted to address the potential of ammonia and hydrogen for shipping industry. The dominant impact was fuel use and related fuel production.	(Evers et al., 2023)
LCA study on the use of LNG hybrid, LNG, green hydrogen, ammonia and methanol fuels	Alternative fuel	Yangtze River bulk carrier	Alternative fuel	N/A	N/A	Chinese-Croatian bilateral project on energy efficiency and environmentally friendly power system options	Explores reducing carbon emissions in the shipping sector while considering economic development, emphasizing cargo growth. LNG hybrid, LNG and methanol are currently suitable options, with green hydrogen and ammonia offering significant carbon reductions of up to 91.3%	(Yan et al., 2023)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
						for inland green ships		
Comparative study of different fuel cell technologies for hydrogen-fuelled ship application	Fuel cell	General cargo vessel	Fuel cell, HT-PEMFC	N/A	N/A	LNG Fuel Gas Supply System for Coastal Ships	The methanol-based system has higher energy and exergy efficiencies but requires more space and has a significantly higher fuel cost compared to the methane-based system at a fixed electrical power output.	(H. Lee et al., 2020)
Comparative LCA study of auxiliary power system using methanol	SOFCs	Commercial vessels	Fuel cell	N/A	N/A	Validation of Renewable Methanol Based Auxiliary Power System for Commercial Vessels	The analysis of fuel alternatives for electricity generation via SOFC indicates that bio-methanol, along with hydrogen from cracking and electrolysis, offers a highly attractive and environmentally superior option compared to conventional engines as auxiliary generators.	(Strazza et al., 2010)
Economic analysis of LH2 tanker, fuelled by hydrogen	H2 powered engine	Tanker	H2 powered engine	N/A	LH2 tanker can cover the capital cost within 2.5 years.	N/A	LH2 can cover its capital cost within 2.5 years under favourable maritime shipping conditions, making it a valuable contribution to the green hydrogen economy.	(Alkhaledi et al., 2022)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
LCCA and LCA of inland waterway ships (electrification)	Electrification ship	Inland waterway ships	Electrification technologies	Electrification of inland vessels results in a GHG reduction of up to 64% and NO_X emission reduction of up to 99%	N/A	Green Modular Passenger Vessel for Mediterranean (GRiMM)	PV cell battery-powered ships are the most environmentally friendly, resulting in significant GHG and NO_X emission reductions, but diesel engines remain the most economical choice in the absence of incentives for green technologies in Croatia.	(Perčić et al., 2021)
LCA and economic analysis of ammonia for short sea shipping	Ammonia	General cargo	N/A	Up to 42.8%	Brown ammonia is cheaper, green NH3 is not cost-competitive today	N/A	Brown ammonia has comparable or worse CO_2 emissions than marine diesel oil (MDO), blue ammonia meets the IMO 2030 target, and green ammonia from wind energy significantly reduces CO_2 emissions but is currently less economically feasible.	(Zincir, 2022)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
LCA of biofuels in shipping industry	Biofuels	Ro-pax ferry	Biofuels	50% GHG reduction, compared to fossil fuels	N/A	N/A	The biofuels offer better overall environmental outcomes than the diesel route, although the use of biofuels can reduce global warming potential while increasing environmental impact in other categories such as eutrophication and primary energy use.	(Bengtsson et al., 2012)
LCA of hydrogen and ammonia for maritime industry	Hydrogen and ammonia	Trans-oceanic freight ship and tanker	Hydrogen and ammonia	Up to 33.5%, compared to heavy fuel oil	N/A	Natural Sciences and Engineering Research Council of Canada	Using hydrogen and ammonia significantly reduces GHG emissions and global warming impact, with the potential for emissions reductions.	(Bicer & Dincer, 2018)
Comparative LCA study of different alternative fuels	Alternative fuels	Nearshore ferry	Alternative fuel	10% GWP higher if grey hydrogen is used, compared to MGO and LNG	N/A	N/A	Hydrogen has higher GHG emissions during production, it outperforms in other environmental categories, making it a promising future ship fuel; it is suggested that carbon capture methods be used to reduce hydrogen's production emissions,	(G. N. Lee et al., 2022)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Emission reduction analysis for using batteries in ship power system	Batteries	N/A	Batteries	Around 9%	N/A	N/A	Batteries can reduce emissions by optimizing diesel generator operation and sensitivity analysis shows factors such as battery round trip efficiency, minimum generator load, and battery characteristics have varying impacts on emissions reduction.	(Peralta P et al., 2019)
LCA study of battery powered ships	Batteries	Ro-Pax	Batteries	Up to 35.7%, compared to diesel powered vessels	N/A	N/A	Using a battery-driven propulsion system reduced global warming potential by 35.7%, but also highlighted that the source of electricity generation for the batteries is crucial in determining the overall environmental benefits of such a switch in marine transportation	(Jeong et al., 2020)
Evaluating the environmental and economic feasibility of hydrogen-powered vessels in the context of international and regional decarbonization goals	Hydrogen-powered propulsion	Ferry, trawler, tug	Hydrogen-powered propulsion	Up to 80% GHG reduction	60% life cycle costing savings	N/A	Hydrogen-fuelled vessels can lead to over 80% emission reduction and approximately 60% life cycle cost savings compared to conventional diesel-powered ships.	(H. Wang et al., 2023)

Criterion 1 Study focus	Criterion 2 Technology type	Criterion 3 Ship type	Criterion 4 Technology potential	Criterion 5 GHG abated	Criterion 6 Cost of technology	Criterion 7 Case study/ project	Criterion 8 Result in general	Reference
Hydrogen fuelled ships	Hydrogen-powered propulsion	LNG carriers	Hydrogen-powered propulsion	N/A	N/A	N/A	Electrolytic hydrogen production is not always the most environmentally responsible option, with coke oven gas hydrogen supply method producing the highest carbon emissions. For hydrogen fuel cell ships, the optimal sailing speed falls between 14 and 14.5 knots	(Z. Wang et al., 2023)
A novel methodology called Live-LCA for overcoming limitations in conventional lifecycle assessment practices. Assessing the feasibility of solar-electric propulsion ships as an environmentally friendly solution for maritime transport in accordance with global environmental conventions and goals.	PV-electric propulsion	PV-electric ship	PV-electric propulsion	N/A	N/A	N/A	The performance of these systems is influenced by climate conditions and national power production methods. The PV-equipped ship reduced 40,812 kg CO_2eq. per year in Brazil, while achieving greater reductions in India and Australia due to coal-based power production.	(Park et al., 2022)
New LCA methodology for shipping industry	Hydrogen fuel cell	1932 small vessels under 500 GT	Hydrogen fuel cell	N/A	N/A	Clean Maritime Demonstration Competition	All hydrogen fuel cell except from coal (fossil) can reduce all environmental potentials (GWP, AP, EP) compared with LNG and diesel. Parametric trend LCA can be used to evaluate the environmental performance of vessel fleet	(Jang et al., 2022)

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Solar energy on passenger ships	Solar energy	Passenger ships	Solar energy	N/A	PV systems require low maintenance cost	N/A	Energy savings and emission reduction can be achieved by using PV (solar photovoltaic) plants.	(Abdullah-Al-Mahbub et al., 2023)
Ammonia and fuel cell in shipping industry	Ammonia and fuel cell	Cargo vessels	Ammonia and fuel cell	N/A	N/A	N/A	Ammonia/ammonia fuel cells can help the shipping industry halve its CO_2 emissions	(Gallucci, 2021)
Literature review on ships' emissions, aftertreatment systems	Aftertreat-ment system	Cargo vessels	Aftertreat-ment system	N/A	N/A	N/A	Reviews the alternative fuels and engine emissions; summarizes the methods that can reduce emissions of marine engines	(Feng et al., 2022)
Emission factor estimation (on board emission measurements), biofuel (from cooking oil)	Alternative fuels for maritime industry	Bulk carrier	Use of biofuel onboard	N/A	N/A	Oldendorff Carriers GmbH & Co. KG	Biofuel can have positive impacts for bulk carriers in the short-term future	(Stathatou et al., 2022)